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Methodology for an experimental drift velocity determination using a µTPC. Example in a 700mbar 95%He+5%CO_2 mixture

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Abstract: The micro-irradiation, neutron metrology and dosimetry laboratory of the Institute for Radiological Protection and Nuclear Safety (IRSN) is a National Metrological Institute associated laboratory, is in charge of the neutron fluence distribution references and produces neutron reference fields.
The laboratory is developing a primary neutron-detector based on the use of Time Projection Chamber technology. This detector, called µTPC, can use different types of gas over a range of precise pressures. The analysis of µTPC data requires the determination of both the energy and the track direction of the recoil particles. The drift velocity in the gas is a key data point for analysis. Based on several experimental measurements performed using the µTPC with monoenergetic neutron fields, a direct methodology to determine the drift velocity can be proposed. These results are compared with those found using theoretical drift velocity from the Magboltz simulation.

Keywords -- Neutron, Fluence, Time Projection Chamber (TPC), drift velocity, Magboltz

I. INTRODUCTION

The French Institute for Radiological Protection and Nuclear Safety (IRSN), as a designated institute by the French National Metrological Institute (LNE) [1], develops primary measurement standards using a Time projection detector (µTPC). Data collected using this detector leads to nuclear recoil track reconstruction. For this purpose, the analysis requires a precise value for drift velocity. The MAGBOLTZ simulation calculates an initial value of 9.55 µm/ns. However, after the analysis of µTPC data, this value appears to be incorrect. Taking into account the known physical properties of neutron scattering, an experimental method is proposed to determine the drift velocity in the detector.

II. THE LNE-IRSN/MIMAC MICROTPC DETECTOR

A. *Description*

In the neutron detection field, there exists at least two models of µTPC. The LNE-IRSN-MIMAC detector (also called µTPC) is a time projection chamber that uses a pixelated Micromegas anode, coupled to a fast-self-triggered electronic system. Figure 1 is a schematic illustration of the µTPC working principle with the charge collection and the ion track. Each event has a charge collection profile measured by the grid (bottom left in figure 1) and a series of $Nb_{Slices}(i_{event})$ obtained on the pixelated anode (bottom right in figure (1)).

The detector active zone is a rectangular parallelepiped volume measuring 10.8 cm x10.8 cm x17.7 cm. It is filled with an adjustable gas mixture. A homogeneous electric field of adjustable intensity is applied through a wired field cage. This field draws the electrons toward the grid.

The total charge is collected by the grid. In the amplification zone, which is located between the grid and the anode, there is a higher electric field which produces a Townsend avalanche, which amplifies the signal. The anode is composed of 256 strips in each direction with a pitch of 424 µm. The Micromegas pixelized anode is read at a frequency of 50 MHz using a self-triggered electronic system developed at the Subatomic Physic and Cosmology Laboratory in Grenoble (C.N.R.S/L.P.S.C, France) [4].

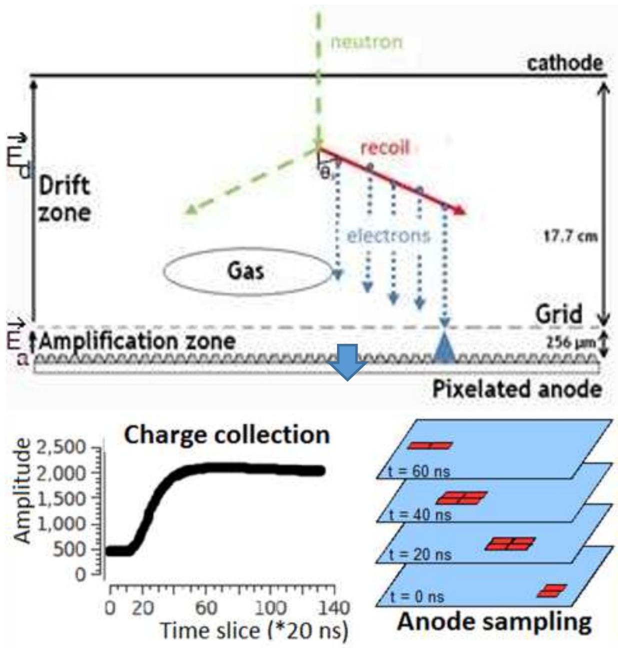


Fig 1 :Schematic view of the microTPC working principle

The µTPC can use different types of gas at a precise pressure within a limited range. This limitation is due to specific detector constraints. The gas mixture used here was 95% ^4He and 5 % CO_2 at an absolute pressure of

700 mbar. The mixture is pre-made by the supplier which introduces a certain level of uncertainty, but the same shipment is used for all our experiments to guarantee reproducibility.

The analysis presented below is done with data from a measurement campaign on 1.2 MeV and 5 MeV monoenergetic neutrons fields. The nuclear recoils of interest are those of the alpha, which are the result of (n, α) elastic scattering reactions.

B. Use of the µTPC in neutron metrology

In neutron metrology, the µTPC detector can also be used for the determination of the incident neutron energy based on knowledge of the kinematic parameters of the scattering reaction. These parameters are used in equation (1) for the neutron energy (E_n) computation, where (m_n) and (m_r) are respectively the neutron and the recoil nucleus mass, (E_r) is the kinetic energy of the nuclear recoil and (Θ_{nr}) is the angle between the incident neutron direction and that of the nuclear recoil.

$$E_n = \frac{(m_n + m_r)^2}{4.m_n.m_r} \cdot \frac{E_r}{\mathrm{Cos}^2(\theta_{nr})} \quad (1)$$

Each of these parameters can be deduced from the acquired raw data. The initial direction of a neutron is imposed by the experimental setup. But it can also be deduced using a statistical approach, as this reaction conforms to a specific angular distribution as a function of $\cos(\Theta_{nr})$. Obviously, the neutron energy calculation should not be dependent on the scattering angle. In the following, to simplify, we note:

$$P_z = \cos(\theta_{nr}) \quad (2)$$

We can assume an approximate P_z by the ion direction component relative to the detector main symmetry axis (positive from cathode to anode). It can be justified by the fact that, in the neutron fields analyzed in the present work, the angle between the detector *z* axis and the direction of an emitted neutron is statically limited to +/- 1°. Moreover, this distribution is symmetrical with respect to 0°. This simplification has a negligible impact on the method presented below. The full metrological fluence measurement capability is described in reference [5].

C. Available observable quantities and associated corrections

From the raw data acquired by the detector, the recoil ionization energy is computed, event by event, from the associated charge collection profile. In order to estimate the recoil kinetic energy E_r, the following sequence is applied: first, the ionization energy $E_{ionization}$ is obtained from the charge collection profile by applying a linear calibration, then E_r is deduced from $E_{ionization}$ using the Ionization Quenching Factor (*IQF*) which is ionization energy dependent [6].

A three-dimensional reconstruction of the charged particle track is also performed event by event [7][8][9]. The pixelated anode provides X and Y direction coordinates. The third direction coordinate *Z* is deduced from the anode read period ΔT, the number of slices $Nb_{Slices}(i_{event})$ of the associated event and the drift velocity V_{Drift} using the relation given by (3):

$$Z = Nb_{Slices}(i_{event}).\Delta T.V_{Drift} \quad (3)$$

The produced electron drift velocity is a key data for the computation of the recoil ion track angle and thus, the neutron energy E_n. Moreover, the correlation between track length and energy deposit is the basis for identifying and selecting alpha recoil events [7][8][9].

D. Drift velocity simulation in the gas mixture

The drift velocity can be simulated by MAGBOLTZ [10] which computes drift gas properties in a given electric field by numerically integrating the Boltzmann transport equation (i.e., simulating an electron bouncing around, inside a gas). The MAGBOLTZ simulation computes the drift velocity by tracking virtual electron propagation step by step. The MAGBOLTZ simulation was performed for the µTPC assuming a uniform electric field of ~156.5 V/cm in the defined gas mixture. The MAGBOLTZ calculated drift velocity was evaluated at 9.55 µm/ns.

III. METHODOLOGY: DETERMINING DRIFT VELOCITY

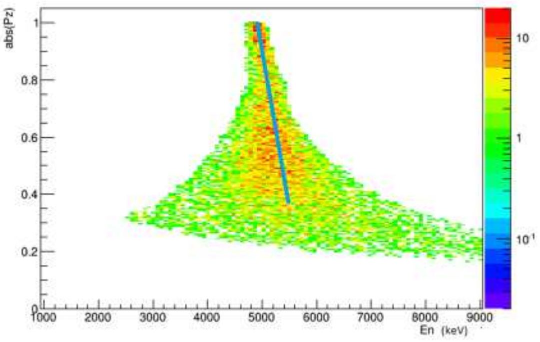
A. Exploitation of the recoil nuclei energy/direction correlation

The proposed methodology is based on the use of the energy/direction correlation for a group of recoil nuclei induced by a monoenergetic neutron field. In the following, we calculate the recoil nucleus energy using the IQF law computed using the TRIM option of the SRIM software [11]. The ionization energy is deduced from the charge collection profile using a calibration of the µTPC carried out using the alpha from the $^{10}B(n_{th},^{7}Li)^{4}He$ reaction [12].

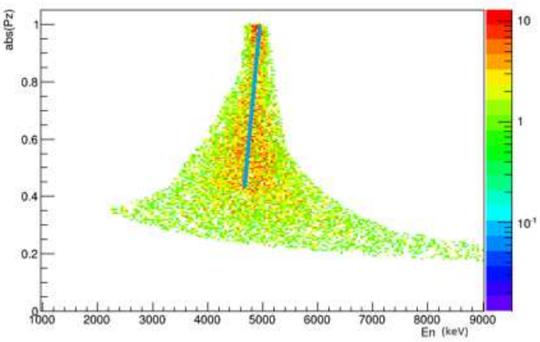
The reconstructed average neutron energy, normally, should not be dependent on the direction of the recoil. But this is not the case if we use the drift velocity calculated by the Magboltz simulation. So, we decided to perform a parametric analysis as a function of V_{Drift} to accurately determine the optimal drift velocity V_{Drift}^{opt}.

We performed several analyses with different drift velocities as input. In the following figure 2, we compare the bidimensionnal histograms linking the computed P_z (on the ordinate) and the computed neutron energy (on the abscissa) for two V_{Drift} value. We observed a loss in resolution when decreasing P_z. This is related to recoils with a smaller track length and therefore a greater difficulty to estimate the initial nuclear recoil direction.

Indeed, electron diffusion becomes an important phenomenon making the estimation of the initial recoil direction more and more difficult. So angles larger than 60° (where $P_z < 0.5$) are not considered for the proposed methodology. The blue line on each graph shows the average neutron energy calculated as a function of P_z.



(a) V_{Drift} =9.55 µm/ns (Magboltz)



(b) V_{Drift} =10.2 µm/ns

Fig. 2. Bidimensionnal histograms of the (E_n(keV), $|P_z|$) distribution for different input drift velocities V_{Drift} (in blue a visual estimation of average) obtained with the IQF correction issued from SRIM/TRIM [11]

Visually, we can see on chart (a) associated with the Magboltz drift velocity estimation (i.e. 9.55 µm/ns), that the calculated average energy increases as P_z decreases. On the other hand, when drift velocity is increased to 10 µm/ns, the calculated energy decreases as P_z decreases (see chart (b)). So, the drift velocity is too high. In order to get accurate quantitative results, a sampling method by band of P_z is proposed. The full methodology used to estimate the optimal drift velocity is presented in the next section.

B. *Methodology: Quantitative V_{Drift} determination*

The following method aims at a systematic and effective determination of an optimal drift velocity. First, for a set of drift velocity values, the calculation of the average neutron energy is performed as a function of the recoil direction P_z. Then, for each drift velocity a straight-line slope is deduced from the curve relating calculated mean energy as a function of recoil direction P_z. So, for each V_{Drift}, a slope can be found through a linear fit on the curve relating the mean neutron energy E_{mean} and the mean direction cosine P_z^{mean}. This approach enables us to build a graph relating slopes with their associated uncertainties as a function of V_{Drift}. Finally, the optimal drift velocity is deduced via the search for a zero slope (which ensured the independence of the mean neutron energy calculation as a function of recoil direction).

The following sampling sequence was applied:

- For a set of V_{Drift} values:
  - A mobile selection zone of $|P_z|$ was defined as [P_z^{min}, P_z^{max}] ensuring a constant statistic for the number of events ($Nb_{EventInPzSlice}$). The mean value P_z^{mean} is determined for each selection zone [P_z^{min}, P_z^{max}].
  - The neutron energy deduced from E_{recoil} and angular scattering is computed for each event. By $|P_z|$ zone, a gaussian fit on the projected histogram is performed to get the E_{mean} value. Uncertainties on E_{mean} is estimated by the sigma of the gaussian fit done with ROOT software [13].
  - A linear fit of $E_{mean} = f(P_z^{mean})$ for a given drift velocity value is determined leading to $Slope(V_{Drift})$ and its associated uncertainty $\Delta Slope(V_{Drift})$ deduced from the linear fit for this drift velocity.
- Resulting slopes are then plotted on a graph as a function of V_{Drift}. A linear fit is performed on that graph which enables the deduction of the optimal V_{Drift} value.

This methodology was applied to two measurements performed at the National Physical Laboratory (N.P.L, Teddington, U.K.) in monoenergetic neutron fields at 5 MeV and 1.2 MeV and for different V_{Drift} values.

We applied the methodology to the 565 keV monoenergetic neutron field data analysis. The results were more difficult to obtain and at a much higher uncertainty level. These difficulties have various possible causes:

- First, at that neutron energy, the differential cross section of the (n, α) reaction peaks steeply at 0° i.e. at P_z=1, leading to a very limited zone for the linear fit.
- Secondly, we suspect a high relative bias induced by the choice of the applied *IQF* curve. This point will be discussed briefly in section 4 and more precisely in a future publication.
- Third, the reduced track lengths result in poor angular resolution.

We realized a parametric analysis as a function of the target statistic in the selection zone. The final impact of this target statistic on the average slope associated to a given drift velocity appears to be negligible.

C. *Results: 5 MeV monoenergetic neutrons field*

Figures (3) and (4) show results of the methodology with the 5 MeV neutron field. Figure (3) presents E_{mean}

variation as a function of P_z^{mean} for different V_{Drift} values. For each V_{Drift}, a *Slope*(V_{Drift}) can be derived with its associated uncertainty Δ*Slope*(V_{Drift}) from the fit realized on the series of points (P_z^{mean}, E_{mean}) computed for that V_{Drift} taking into account the ΔE_{mean}.

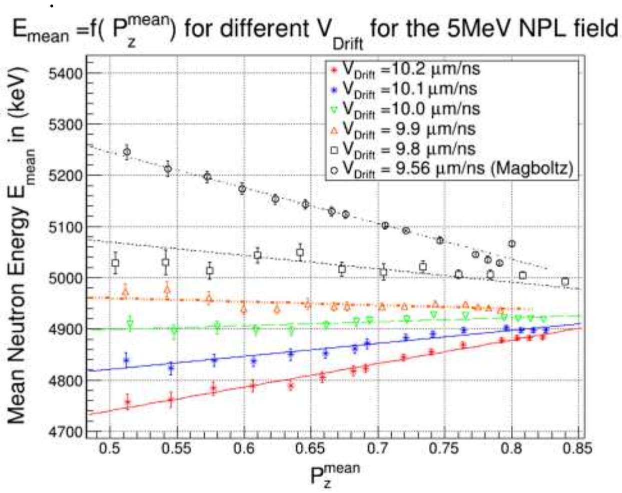


Fig.3: Multigraph showing (P_z^{mean}, E_{mean}) points for different V_{Drift} values and the associated linear fits using measurements from the 5MeV NPL reference field

The results of the fit for each value a V_{Drift} are listed in the table 1:

TABLE 1

FIT RESULTS FOR EACH DRIFT VELOCITY

V Drift (µm/ns)	Slope(+/-ΔSlope) (keV)	Offset(+/-ΔOffset) (keV)
10.2	459.6(+/-24.0)	4510.5 (+/-18.3)
10.1	253.4(+/-22.3	4694.3 (+/-17.1)
10.0	76.2(+/-23.7)	4860.6 (+/-18.0)
9.9	-68.0(+/-28.0).	4994.0 (+/-20.5)
9.8	-260.8(+/-23.6)	5199.8 (+/-19.7)
9.56	-695.7(+/-27.0)	5592.8 (+/-19.5)

As shown in figure 4, the set of (V_{Drift}, *Slope*(V_{Drift})) and their associated uncertainties Δ*Slope*(V_{Drift}) are plotted on a second graph. A second linear fit is then applied to this set of points taking uncertainties into account. The optimal value of V_{Drift} is defined as a slope value equal to zero. From this fit, we estimate an accurate V_{Drift} value of 9.95µm/ns

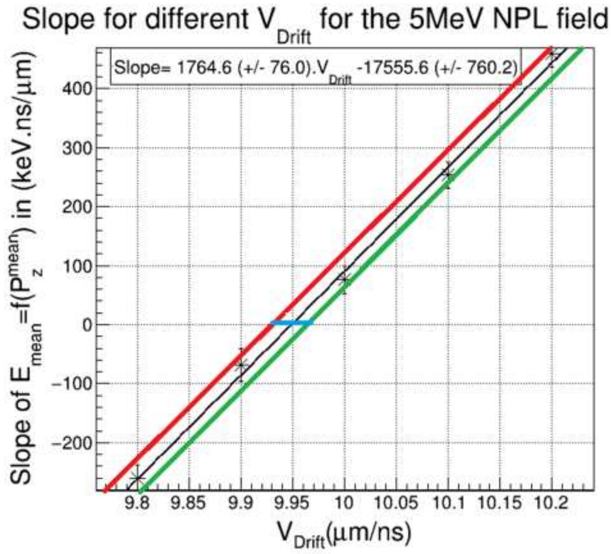


Fig.4: Graph showing the set (V_{Drift}, Slope(V_{Drift})), their associated uncertainties ΔSlope(V_{Drift}) and the associated linear fits (in red: fit with Slope+ΔSlope, in green : fit with Slope-ΔSlope, in black: the initial fit) for the 5MeV NPL reference field.

To quantify the uncertainty associated with this estimation, we perform two additional fits:

- One for the set of points given by (V_{Drift}, *Slope*(V_{Drift}) + Δ*Slope*(V_{Drift})),
- Another for the set of points given by (V_{Drift}, *Slope*(V_{Drift}) - Δ*Slope*(V_{Drift})),.

With this approach, the optimal V_{Drift} value is estimated to be in the range [9.93-9.96] µm/ns

D. Results: 1.2 MeV neutrons

The same methodology was then repeated on the measurements performed at 1.2 MeV reference field. From this analysis, we can estimate an optimal V_{Drift} value close to 10.07µm/ns. With the uncertainty approach described above, the optimal V_{Drift} value is estimated to be in the range [10.06-10.09] µm/ns.

IV. DISCUSSION

The drift velocity in a µTPC is a key parameter in the proper reconstruction of charged particles tracks. It has been shown that the drift velocity value computed by the Magboltz simulation leads to a result incompatible with the physics which requires the mean average energy to be constant as a function of P_z.

The drift velocity in a gas mixture (95.0%He + 5.0% CO_2) was determined using measurements in two monoenergetic neutron fields at 5 MeV and 1.2 MeV. Results were compared with the Magboltz simulation.

Some differences in V_{Drift} estimations from both fields were observed:

- V_{Drift_opt}(5 MeV) is between 9.93 and 9.96 µm/ns, 4.1% *higher* relative to the Magboltz estimation (9.55 µm/ns),

- V_{Drift_opt}(1.2 MeV) is between 10.06 and 10.09 µm/ns, 5.3% *higher* relative to the Magboltz estimation.

A V_{Drift} sensitivity study performed with Magboltz near the nominal operating point (95%He/ HV_{Drift}= 2770V/ 700 mbar/20°C) shows that V_{Drift} sensitivity relative to:

A) stoichiometry is +/- 1.2% for +/-1% of ^{4}He,
B) high voltage is 0.046% per Volt,
C) pressure is 0.24% per mbar,
D) temperature is 0.28% per °C.

Combining these sensitivities with the associated uncertainties leads to a cumulative relative error of 0.31% on V_{Drift}. Therefore, we conclude that it is not possible to attribute the gap of 1.2% between the two estimations, to variations in the experimental conditions, alone, between the two measurements.

One possible explanation for this gap could stem from the assumption, in the Magboltz simulation, of a uniform electric field. Indeed, simulations previously carried out in reference work [14] using a different gas mixture have demonstrated that there was a slight deformation of the electric field near the grid. As the tracks in the 5 MeV field are longer, one can postulate a slight difference in the influence of this deformation on the tracks in the drift cage.

Another explanation could come from the use of an Ionization Quenching Factor (IQF) curve computed using the TRIM option of SRIM [11]. Indeed, some measurements [9] done at the AMANDE facility lead us to believe that the TRIM software, as it is designed, underestimates the IQF at low recoil energy. We tested the application of a preliminary IQF curve to the V_{Drift} determination process and this led to an additional increase in the drift velocity.

Even though some additional measurements are needed to provide a consolidated estimation, increasing the drift velocity compared to the Magboltz estimation is a necessity.

V. Conclusion and Perspectives

A drift velocity measurement with a Time Projection Chamber has been performed in this study. The measured value is slightly higher, around +5%, above the value computed by Magboltz. The sensitivity study cannot explain the discrepency, in state. In order to conclude, the proposed method could be completed and improved by other studies:

- Additional measurement of the drift velocity with the cathode signal as in reference [15],
- Further measurements using the AMANDE monoenergetic neutrons fields with enhanced statistics
- Using the charge collection profile on the anode grid of the µTPC as in reference [16].

A better estimation of IQF through experimental campaigns is required to obtain a consolidated estimation of the drift velocity.

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References

[1] V. GRESSIER et al., “New IRSN facilities for neutron production”, NIM A, 505 370-373, 2003.
[2] D. SANTOS et al., “MIMAC: MIcro-tpc MAtrix of Chambers for dark matter directional detection”, Proceedings of the 4th International Conference on Directional Dark Matter Detection CYGNUS2013, held in Toyoma (Japan), 2013.
[3] I. GIOMATARIS et al., “Micromegas in a bulk”, NIM A, vol. 560, pp. 405-408, 2006.
[4] O. BOURRION et al., “Data acquisition electronics and reconstruction software for real time 3D track reconstruction within the MIMAC project”, JINST 6 C11003, 2011.
[5] M. PETIT et al ; “A Time projection chamber (TPC) : a primary detector concept for neutron metrology between 24 keV and 19 MeV“, to be published
[6] O. GUILLAUDIN et al., “Quenching factor measurement in low pressure gas detector for directional dark matter search“, EAS Publ.Ser. 53 (2012) 119-127.
[7] D. MAIRE et al., “First Measurement of a 127 keV Neutron Field with a -TPC Spectrometer”, IEEE TNS (2014), Volume: 61 , Issue: 4 , Part: 2, pp. 2090-2096.
[8] D. MAIRE et al., Rad. Prot. Dos., Vol. 161, Nos 1–4, pp. 245-248 (2014).
[9] B. TAMPON, PhD Thesis, (2017), “ Qualification expérimentale de la µTPC LNE-IRSN-MIMAC comme instrument de référence pour les mesures en énergie et en fluence de champs neutronique entre 27keV et 6,5 MeV “
[10] S.F. BIAGI, ”Monte Carlo simulation of electron drift and diffusion in counting gases under the influence of electric and magnetic fields”, Nuclear Instruments and Methods in Physics Research A 421 (1999) 234—240,
[11] J. F. ZIEGLER, J. P. Biersack and U. Littmark, Pergamon Press New York (1985), www.srim.org.
[12] D. SANTOS et al. ,”Neutron spectroscopy from 1 to 15 MeV with Mimac-FastN, a mobile and directional fast neutron spectrometer and an active phantom for BNCT and PFBT”, EPJ Web of Conferences 231, 05003 (2020)
[13] « ROOT a Data analysis Framework | ROOT a Data analysis Framework ». https://root.cern.ch/
[14] G. PUILL, " Le Développement de Micromégas, un nouveau détecteur gazeux de position à microgrille", PhD Thesis 2000 directed by B. TAMAIN
[15] C. COUTURIER et al., “Cathode signal in a TPC directional detector: implementation and validation measuring the drift velocity”, Journal of instrumentation, 2017, 12 (11), pp.P11020
[16] J. BILLARD et al.,” Measurement of the electron drift velocity in CF4 and CHF3 gas mixtures in the context of upcoming directional Dark Matter detectors”, Journal of instrumentation, May 2013 9(01)