

# A MODIFIED SETUP FOR MEASURING THE FIRST IONIZATION COEFFICIENT OF TISSUE EQUIVALENT GASES AT LOW PRESSURE

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## ABSTRACT

In our previous works, measurements of the first Townsend ionization coefficient,  $\alpha$ , for pure nitrogen and isobutane at atmospheric pressure as a function of the reduced electric field were carried out in the range of 145 to 194 Td to prevent the chamber from electrical discharges. In order to increase this upper limit, the setup was modified for operating at low pressure. The detector has a Resistive Plate Chamber-like configuration where the primary ionization is produced by the incidence of nitrogen pulsed laser beam on an aluminum electrode. To validate the technique, measurements of the first Townsend ionization coefficient in nitrogen as a function of the reduced electric field were carried out at atmospheric pressure and at 100hPa, as this is an extensively studied gas with well-established data. Good agreement among our results, data from the literature and Magboltz simulations, leading us to extend our method to Tissue Equivalent (TE) gases whose  $\alpha$  is unknown. Preliminary measurements of  $\alpha$  in a methane-based TE gas (CH<sub>4</sub> - 64.4%, CO<sub>2</sub> - 32.4% and N<sub>2</sub> - 3.2%) are also presented.

## 1. INTRODUCTION

The key quantity to understand and describe an avalanche in a Proportional Counter is the first Townsend ionization coefficient,  $\alpha$ . Not only is this parameter important in the field of gaseous detectors, but it is also fundamental for validating electron collision cross sections and for modelling discharges. The increasing demand for data on  $\alpha$  in complex molecular gases is due to their widespread application as filling gases in Resistive Plate Chambers (RPCs), microstructure detectors and Tissue Equivalent Proportional Chambers (TEPCs), which are widely used in experimental microdosimetry. Nevertheless, measurements for these gases are scarce in the literature. For instance, there are no reports of  $\alpha$  in isobutane in the E/N range of 200 – 500 Td (1 Td = 10<sup>-21</sup> V·m<sup>2</sup>), even though it is commonly employed as

quenching gas in detectors operating in avalanche and streamer modes and it is the major component of the tissue-equivalent gas mixture (TE gas) proposed by Bronic and Grosswendt [1]. Below this range, the only available data are those published in our previous works [2 - 4], employing atmospheric pressure. In order to extend the range of investigation of the first Townsend ionization coefficient, the experimental setup was modified for operating at low pressures.

After the improvement, our apparatus was crosschecked and the method validated by measuring  $\alpha$  in nitrogen and comparing it with the available literature and Magboltz simulations. This gas was adopted owing to the well-established sets of  $\alpha$  value in  $N_2$  that have been reported extensively [5-7]. Another advantage of choosing nitrogen is its application in TEPCs, both pure [8] and as a component of TE gases. Besides  $N_2$ , these mixtures are made up of a hydrocarbon, such as isobutane [1], propane [9] or methane [10, 11], as the main component, and carbon dioxide. Although the first Townsend ionization coefficient in constituents of TE gases other than isobutane have been studied by several authors in a wide density-normalized electric field range [12-14], reports on  $\alpha$  in these mixtures are still lacking. Therefore, the results presented here will enable us to apply our technique to TE gases within the reduced electric field range where  $\alpha$  is unknown.

## 2. EXPERIMENTAL SETUP

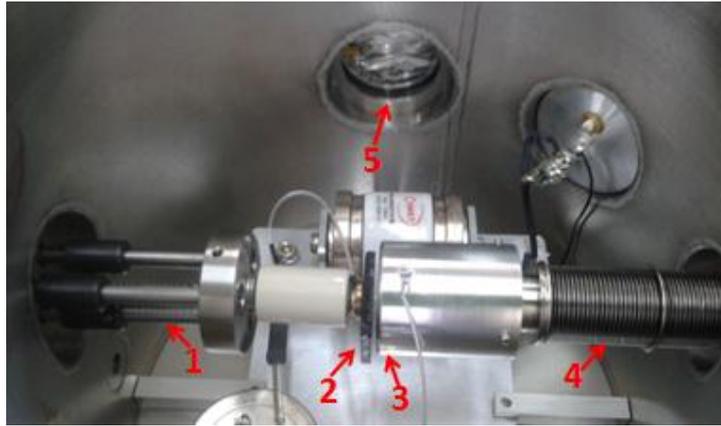
Our setup is basically an RPC-like cell constituted by two parallel electrodes: the cathode was made by an aluminum cylinder with a diameter of 40 mm and the anode by a glass plate 3.5 mm thick with an area of  $32.5 \times 32.5 \text{ mm}^2$  and a resistivity of  $2 \times 10^{10} \Omega \cdot \text{m}$ . The anode was fixed on a brass cylinder with a diameter of 14 mm to allow its polarization by employing a Bertan<sup>®</sup> 225-30 R high voltage supply. A stainless steel chamber isolates the RPC-like cell from the atmosphere and is filled with the gas under study. The inner elements of the setup are shown in Fig. 1.

The parallelism of the electrodes defining the gas gap was adjusted by using three Mitutoyo<sup>®</sup> 189 micrometers connected to the anode and a Huntington<sup>®</sup> L2241-2 linear motion micrometer feedthrough connected to the cathode allowed to change in a simple way the gap thickness. The latter was kept at 1.5 cm for all measurements presented here.

A pulsed nitrogen laser (MNL200-LD LTB<sup>®</sup>) with 337.1 nm wavelength was used to eject the primary electrons from the cathode. The laser beam has a nominal energy of 100  $\mu\text{J}$ , a size of  $1 \times 2 \text{ mm}^2$  and a pulse duration of 700 ps. The laser pulse repetition rate was fixed at 15 Hz.

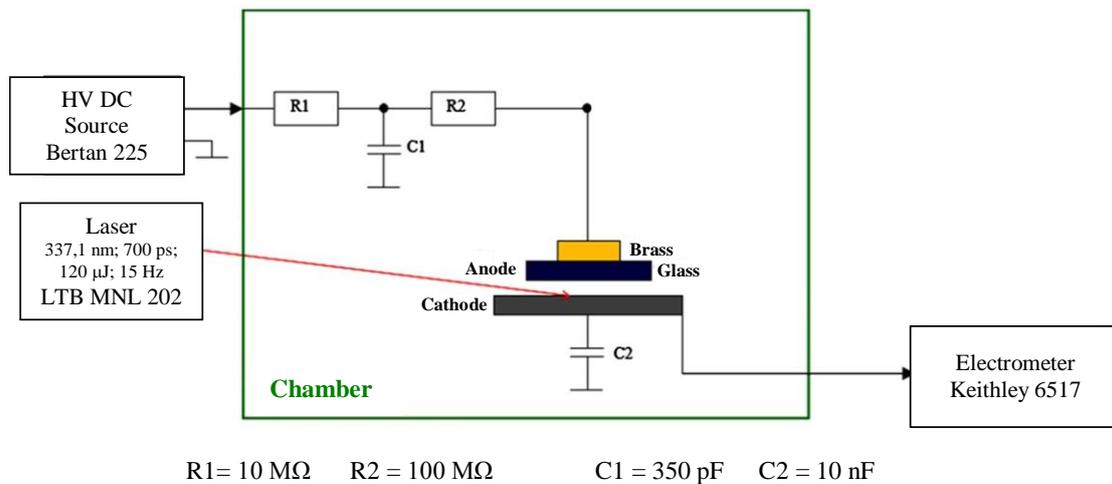
The first Townsend ionization coefficient is determined by the relation between the primary ionization current,  $I_0$ , and the current in avalanche regime,  $I$ . In uniform electric fields, this relation is represented by:

$$\alpha = d^{-1} \ln(I/I_0) \quad (1)$$



**Figure 1: Internal view of the chamber: (1) Mitutoyo® micrometers connected to the (2) glass anode; (3) Metallic cathode fixed on the (4) Huntington® micrometer; (5) Laser beam entrance window, made of synthetic fused silica.**

where  $d$  is the gas gap. The total systematic uncertainty of  $\alpha$  was estimated in 15% due to non-uniformities of the electric field in the gap [2,3]. The average electric current was measured with a digital electrometer Keithley® 6517B (1.0% accuracy) directly connected with the cathode, as represented in Fig. 2.

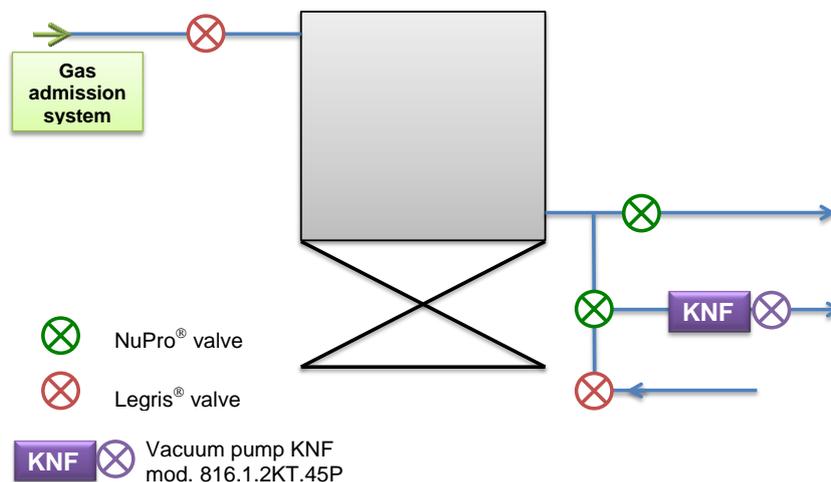


**Figure 2: Schematic drawing of the signal readout circuit.**

## 2.1 Setup Improvements

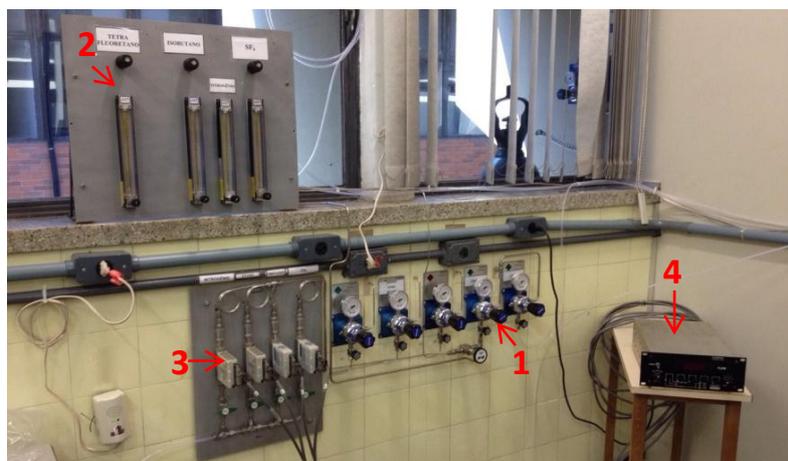
Up to now, all the measurements were carried out at atmospheric pressure. However, this condition limited the upper  $E/N$  and, consequently, restricted the range of investigation of the first ionization coefficient. To obtain higher reduced electric fields, several improvements have been made in the experimental setup in order to operate the chamber at lower pressures. A KNF® 816.1.2KT.45P mini diaphragm vacuum pump was employed to decrease the pressure inside the chamber, which was monitored by a Honeywell® FP2000 pressure transducer, calibrated in the range of 0 to 14.7 psia (0.25% accuracy).

Two Nupro<sup>®</sup> needle valves were fixed in the output gas flow circuit. One was used to liberate the gas from the chamber into the atmosphere in continuous gas flow operation. The other was introduced to let the gas flow to the vacuum pump while working at low pressures. Two Legris<sup>®</sup> needle valves were placed: one just before the chamber entrance and another one in the line connecting the vacuum pump for air admission. All these valves and their connections are shown schematically in Fig. 3.



**Figure 3: Schematic diagram of gas connections where arrows represent the gas flow.**

The gas admission system was also improved, as shown in Fig. 4. A central gas system was installed outside the laboratory. After leaving the cylinder, the gases flow through two Valmig<sup>®</sup> regulating valves and finally to a Valmig<sup>®</sup> needle valve. Next, they can go either to a Cole Parmer<sup>®</sup> manual flowmeter for single gas studies or to an Edwards<sup>®</sup> 825 mass flow controller. The mass flow controllers are connected to an Edwards<sup>®</sup> 1605 multi-channel flow controller unit.

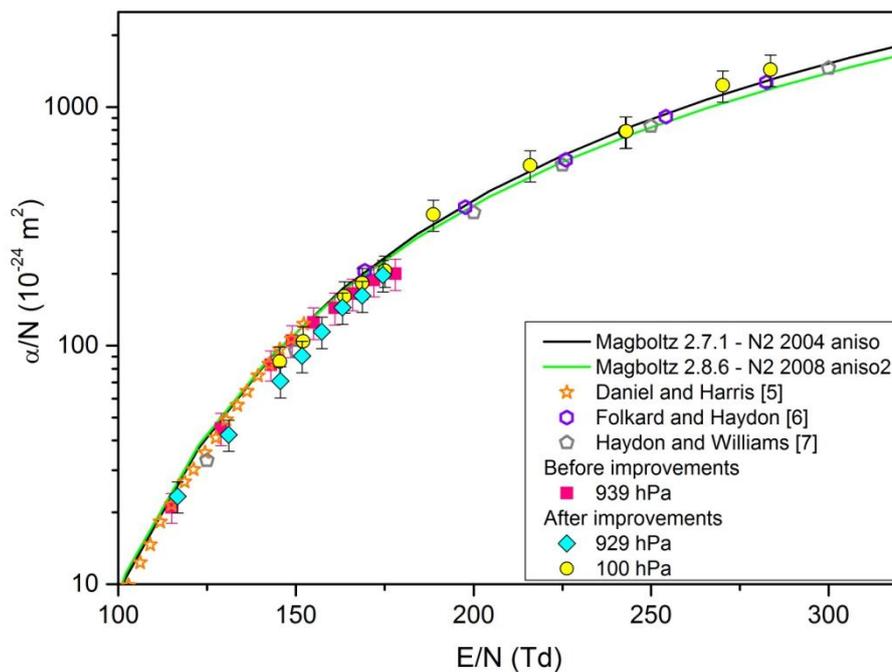


**Figure 4: Gas admission system: 1) regulating and needle valves; 2) manual flowmeters; 3) mass flow controllers and 4) multi-channel flow controller unit.**

In order to crosscheck the modifications of the setup and the method employed, the first Townsend ionization coefficient was measured for nitrogen (Air Products<sup>®</sup> 99,999% purity) due to its well-established value in a wide range of reduced electric fields. Preliminary data on  $\alpha$  in a methane-based TE gas are also presented here. This mixture was made of 64.4% of methane (AGA<sup>®</sup> 99,995% purity), 32.4% of carbon dioxide (Air Products<sup>®</sup> 99,9995% purity) and 3.2% of nitrogen (Air Products<sup>®</sup> 99,999% purity).

### 3. RESULTS

The density-normalized first Townsend ionization coefficient,  $\alpha/N$ , in nitrogen is presented as a function of  $E/N$  in Fig. 5. The results were compared with data from the literature and with Magboltz 2 (versions 7.1 and 8.6) calculations. Magboltz 2, written by Biagi [15, 16], simulates individual electron-atom collisions to determine the electron transport parameters by the Monte Carlo integration technique. The sets of electron cross sections used are “N2 2004” and “N2 2008”. The former is due to Phelps and Pitchford [17] and the latter to several authors [16]. The label “aniso” (version 7.1) and “aniso 2” (version 8.6) [3] refer to the formalisms employed to taking into account anisotropic scattering.

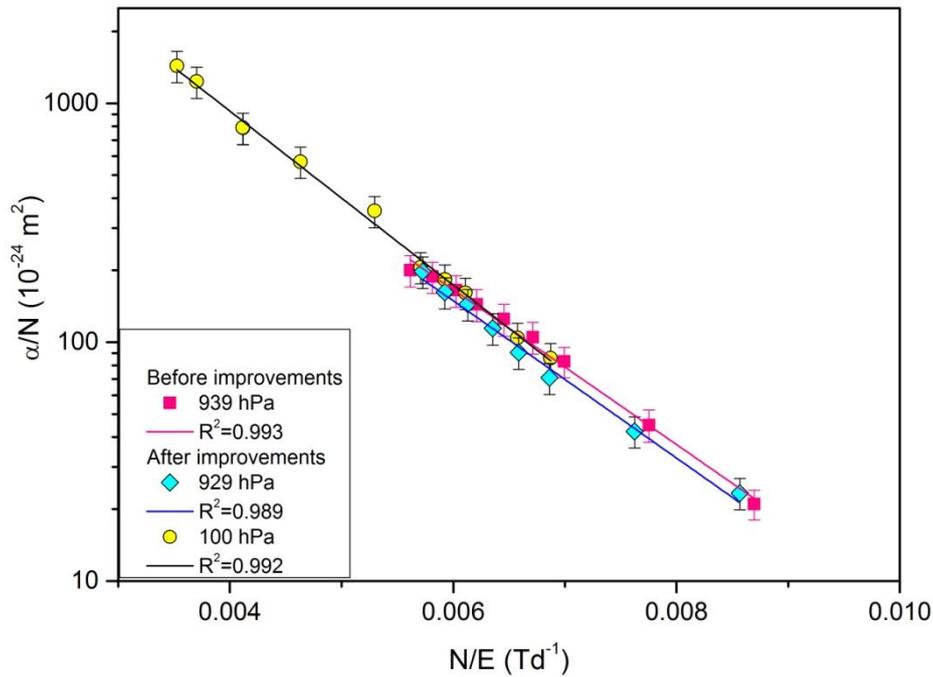


**Figure 5:  $\alpha/N$  as a function of  $E/N$  in  $N_2$ . The results from the literature (open symbols) and the Magboltz simulations (lines) are presented for comparison.**

In the literature, there are several models to describe the relation between  $\alpha/N$  and  $E/N$ . The most well-known one is the Korff parameterization:

$$\alpha/N = A \exp[-B \times N/E] \quad (2)$$

where A and B are constants characteristic of the gas [18]. In order to calculate A and B, curves of  $\alpha/N$  versus  $N/E$  were produced and are presented in Fig. 6. Our results are shown and compared with those from the literature in Tab. 1. The effective ionization potential,  $V_i$ , is determined by the ratio  $B/A$  and it lies between the first ionization potential (for  $N_2$ : 15.58 eV [19]) and the mean energy required to produce ionization in the gas (for  $N_2$ : 36.68 eV [20]).



**Figure 6: Determination of the constants of the Korff parameterization for  $N_2$ . The fit was performed with Origin<sup>®</sup>. The program quantifies the goodness of fit by the coefficient of determination [20] ( $R^2$ ) that is given in the figure.**

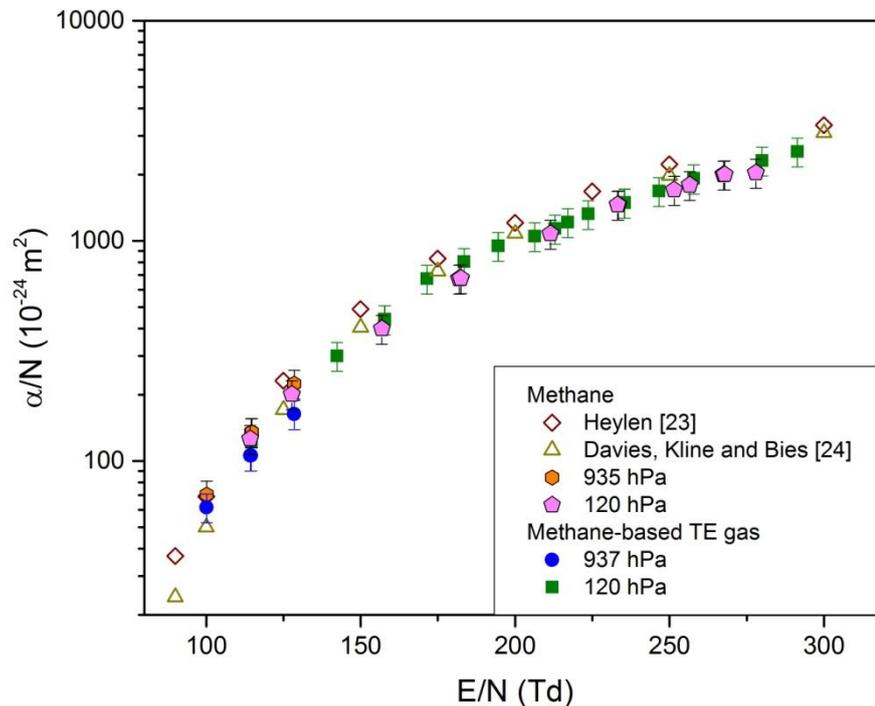
**Table 1: Constants of the Korff parameterization and effective ionization potential for Nitrogen.**

	A ( $10^{-20} \text{ m}^2$ )	B (Td)	$V_i$ (eV)	E/N range (Td)
939 hPa	$1.47 \pm 0.20$	$758 \pm 29$	$52 \pm 7$	115 - 178
929 hPa	$1.41 \pm 0.27$	$840 \pm 16$	$60 \pm 12$	115 - 175
100 hPa	$2.65 \pm 0.23$	$746 \pm 19$	$28.1 \pm 2.5$	145 - 284
Daniel and Harris [5]	2.33	802	34	85 - 152
Haydon and Williams [7]	1.64	771	47	85 - 198

All the results obtained after the chamber modification gathered at both atmospheric and low pressure reproduced our data collected with the previous setup, giving us confidence in the determination of the first Townsend ionization coefficient. The good agreement between our data and those from the literature (Fig. 5, 6 and Tab. 1) further strengthens such a conclusion,

leading us to measure  $\alpha$  in a TE gas ( $\text{CH}_4$  - 64.4%,  $\text{CO}_2$  - 32.4% and  $\text{N}_2$  - 3.2%) where, to the best of our knowledge, no previous study has been published.

The results obtained in the range of 100 Td to 300 Td are depicted in Fig. 7. Due the lack of experimental data, measurements of  $\alpha$  in pure methane are also presented, for the sake of comparison. The behaviour of  $\alpha/N$  in the  $\text{CH}_4$ -based TE gas followed closely the results for pure methane. Indeed, Ségur et al. [22], simulating a cylindrical proportional counter, observed that for  $E/N < 2636$  Td the  $\alpha/N$  in the methane-based TE gas and in pure methane are very similar.



**Figure 7:  $\alpha/N$  as a function of  $E/N$  in the methane-based TE gas ( $\text{CH}_4$  - 64.4%,  $\text{CO}_2$  - 32.4% and  $\text{N}_2$  - 3.2%). Our results and those from literature (open symbols) for pure methane are included for comparison.**

#### 4. CONCLUSIONS

In this work, a modified setup for measuring the first Townsend ionization coefficient of gases at low pressure is described. To crosscheck the method and the improved setup, sets of data on  $\alpha$  in nitrogen at atmospheric pressure and at 100 hPa were obtained. Good agreement was found with data published in the literature and with Magboltz calculations, which lead us to apply this technique to tissue equivalent gases whose  $\alpha$  is unknown. Preliminary measurements of  $\alpha$  in the methane-based TE gas ( $\text{CH}_4$  - 64.4%,  $\text{CO}_2$  - 32.4% and  $\text{N}_2$  - 3.2%) were reported and compared with results for pure methane. The agreement found in their behaviors is the same observed by Ségur et al. in a simulation of a cylindrical proportional counter. Further comparisons with Magboltz 2 simulation are required and are under way.

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