Precision measurement of timing RPC gas mixtures with laser-beam induced electrons

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ABSTRACT: The main goals of a new test facility at Helmholtz-Zentrum Dresden-Rossendorf are precision measurements of the electron drift velocity and the Townsend coefficient of gases at atmospheric pressure in the strongest ever used homogenous electrical fields and the search for new RPC gas mixtures to substitute the climate harmful Freon. Picosecond UV laser pulses were focused into a sub-millimeter gas gap to initialize a defined tiny charge. These gaps are formed by electrodes of low-resistive ceramics or high-resistive float glass. The charge multiplication occurs in a strong homogeneous electric field of up to 100 kV/cm. Electron-ion pairs were generated in a cylindrical micro-volume by multi-photon ionization. The laser-pulse repetition rate ranges from 1 Hz to a few kHz. The RPC time resolution has been measured for different gases. First results of the Townsend coefficient at 100 kV/cm show a strong disagreement between the present measurement and Magboltz simulations for the typical timing RPC gas mixture C₂F₄H₂/SF₆/i-C₄H₁₀, while the measured electron drift velocities are in a good agreement with the model predictions.

KEYWORDS: Lasers; Gaseous detectors; Resistive-plate chambers; Charge transport and multiplication in gas

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1 Introduction

The application of ultraviolet (UV) laser beams for investigation, calibration and surveying of gas filled detectors has been reported first for wire chambers [1, 2] and later on for trigger Resistive Plate Chambers (RPCs) [3–5]. The development of timing RPCs [6] and phenomenological interpretations [7] revealed open questions about the avalanche generation in narrow gas gaps below 1 mm at electrical field strengths of up to 100 kV/cm in different gas mixtures at atmospheric pressure. Measurements of nitrogen and isobutane gas parameters at atmospheric pressure were reported in [8, 9] for a sub-millimeter gas gap and at an electrical field strength of about 50 kV/cm, and in [10–12] at low gas pressure and with few millimeter gaps. Gas parameters were obtained under the assumption that Paschen’s law is absolutely valid for all gases and at sub-millimeter drift paths. This report presents a precision measurement of the electron drift velocity and the effective Townsend coefficient for the timing RPC gas mixture C$_2$F$_4$H$_2$/SF$_6$/i-C$_4$H$_{10}$. In a sub-millimeter gas gap the electric field strength was set to 100 kV/cm. A strongly focused UV laser pulse of picosecond duration was applied at different positions above the read-out electrode.

The present report is organized as follows: section 2 describes the generation of the micro-plasma and its application in gaseous particle detectors. Section 3 describes the gas parameters obtained with the narrow-gap timing RPCs. Finally, section 4 summarizes our results and gives a short outlook.

2 Experimental setup

Two kinds of gas filled radiation sensitive detectors were built. A drift tube was used to calibrate the electron generation with the UV pulses, and a timing RPC was used to measure gas parameters under working conditions.
2.1 Micro-plasma generation

A schematical drawing of the UV light generation is shown in figure 1. This device was assembled in the Laser Particle Acceleration division of the Helmholtz-Zentrum Dresden-Rossendorf. An Yb:KGW laser generates infrared light ($\lambda = 1028$ nm) of sub-picosecond pulse width. The pulse polarization is switched in a downstream Pockels cell with a frequency from 1 Hz to 1 kHz. The Brewster window behind the Pockels cell selects the different polarization states. The horizontally polarized pulses were fed into an optical amplifier. The amplification increases the pulse energy up to few microjoules. During amplification the pulse width increases from 250 fs to 1.85 ps. The subsequent cascade of two second harmonic generators shifts the wavelength into the UV ($\lambda = 257$ nm). To guarantee the long-term stability of the light pulses this part of the facility is encapsulated and stabilized at room temperature. In the next step the light is focused into the RPC. It needs special effort to create a narrow beam envelope at the final focal plane ($F_5$) without streaking the narrow RPC electrodes, located in the center of the detector box (see figure 2). The following optical parameters were obtained at the focal plane: Rayleigh-length ($554 \pm 67$ $\mu$m), horizontal radius ($11.3 \pm 2.2$ $\mu$m), vertical radius ($16.7 \pm 1.1$ $\mu$m). To guarantee high positioning accuracy all parts of the optical system are fixed to a vibration-cushioned and stiff desk for high precision optical experiments. The laboratory is air-conditioned (room temperature 22°C, humidity ≤ 40%) and the measurement setup is additionally covered by a laminar flowbox. To define the focus position with an accuracy of better than 5 $\mu$m with regard to the optical setup the detector is mounted to a 3D micrometric adjustment. The focus position and the vertical mapping of the RPC gas gap aperture were obtained by fitting the experimental data of the beam shape. The beam energy is measured continuously at the output of the detector cell. A gas mixture of up to three components may flush through the detector box. Due to the low photon energy of 4.8 eV the gas ionization occurs exclusively in a multi-photon ionization process. A drift tube was used for calibration purposes of the ion-electron-pair production in dependence on the laser energy.
Figure 2. Focusing of the UV light into the sub-millimeter RPC gap (L – lens, F – focal plane). The focal length \( f_5 \) of lens \( L_5 \) amounts to 3 cm. The light intensity is tuned with the attenuators \( A_1 \) and \( A_2 \).

Figure 3. The charge generated by laser induced multi-photon ionization in dependence on the UV pulse energy. The drift tube is filled with Ar/i-C\(_4\)H\(_{10}\) (84%/16%), and the HV potential amounts to 1.6 kV.

detector consists of a cylindrical cathode with a diameter of 12 mm and a small slit to focus the light into the detector volume at a well defined distance to the anode wire. The anode wire diameter amounts to 20 \( \mu \)m. All metallic elements are gold plated, to reduce photo-electron emission. The drift tube is filled with an Ar/i-C\(_4\)H\(_{10}\) (84%/16%) mixture. The working plateau voltage of the drift tube ranges from 1.55 kV to 1.75 kV. The multi-photon ionization process has been measured over a laser energy range of three orders of magnitude. Figure 3 shows the charge measured with the drift tube at a voltage of 1.6 kV in dependence on the laser energy ranging from 5 nJ to 3 \( \mu \)J. The micro-focus was positioned at a distance to the anode wire of 2.5 mm. For absolute calibration an \(^{55}\)Fe X-ray source was used. Ionization of the present gas yields 200 \( \pm \) 20 electrons per photon. Adjusting the laser pulse energy such that the drift tube delivers a signal of similar height as generated by the X-rays requires a laser energy of 24 nJ.
2.2 Timing RPC probes

The gas parameters of the $\text{C}_2\text{F}_4\text{H}_2/\text{SF}_6/\text{i-C}_4\text{H}_{10}$ mixture were measured within a gas gap of 300 $\mu$m width and 2.4 mm length. Beveled edges reduce the breakthrough and increase the geometrical acceptance for the beam envelope. The relative beam energy transmission ($E_P/E_{P_{\text{max}}}$) measurement in dependence on the focus position ($Y$) is shown in figure 4. The geometrical acceptance allows to shift the micro-focus inside the 300 $\mu$m gap along the electrical field by more than 100 $\mu$m. For the two electrodes a parallelism of better than 10 $\mu$m was achieved. The intrinsic time resolution ($\sigma$) is better than 20 ps. Two RPC samples with float glass electrodes (10$^{13}$ $\Omega$ cm) and low-resistive $\text{Si}_3\text{N}_4/\text{SiC}$ ceramics electrodes (10$^9$ $\Omega$ cm) [13] and gap widths of 300 $\mu$m were used. To guarantee a homogeneous field distribution a constant length-to-width ratio of 8 is used for both probes. One electrode is grounded, and the other is connected to the HV supply. The analog signals, capacitively coupled from the anode, were fed to a digital oscilloscope (LeCroy wave runner 6 Zi). A fast photodetector (OPHIR PD10) delivers the timing signal to trigger the data acquisition. Figure 5 shows the RPC with low-resistive ceramic electrodes mounted in a gas-tight detector box.

3 Results

3.1 Electron drift velocity

The electron drift velocity has been estimated from the dependence of drift time vs. drift path for a couple of beam positions set above the read-out electrode in steps of 10 $\mu$m. The micro-focus allows to shift the beam axis in a range of about 100 $\mu$m without streaking the electrodes. The
Figure 5. The ceramics RPC with a 300 µm gap fixed inside the gas-tight detector box (without quartz windows).

Figure 6. The electron drift time in dependence on the drift path length (Y) for the gas mixture C₂F₆H₂/SF₆/i-C₄H₁₀ (85%/10%/5%) at 100 kV/cm. The accuracy of the drift path setting is better than 2 µm, provided the focus is consecutively shifted in one direction. First measurements of the electron drift velocity for a mixture of C₂F₆H₂/SF₆/i-C₄H₁₀ (85%/10%/5%) have been performed with electrical fields between 70 and 100 kV/cm. For the example at 100 kV/cm shown in figure 6 the drift time increases linearly with path length and a straight-line fit delivers a drift velocity of (202 ± 18) µm/ns. This result is in remarkable agreement with Magboltz simulation as reported by Riegler et al. [7].
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3.2 Townsend coefficient

First measurements of the electron multiplication per path length within narrow gas gaps of 300 µm have been performed at a field strength of 100 kV/cm by measuring the influenced charge in dependence on the focus position, cf. figure 7. The low-resistive Si₃N₄/SiC ceramics allows to measure the spectra with a beam pulse repetition rate of about 100 Hz, to be compared to the float glass RPC probe, where only 1 Hz gives undisturbed charge spectra. A fast decrease of the amplitude by one order of magnitude has been observed by increasing the laser frequency from 1 to 10 Hz. Assuming an exponential increase of the avalanche charge in dependence on the drift path, the effective Townsend coefficient amounts to $\alpha_{\text{eff}}(\text{glass}) = (25.4 \pm 1.1) \text{ mm}^{-1}$ and $\alpha_{\text{eff}}(\text{ceramics}) = (20.7 \pm 1.1) \text{ mm}^{-1}$ for glass and ceramics electrodes, respectively. The results of our measurements are in evident disagreement to both calculations with the Magboltz transport code, $\alpha_{\text{eff}}(\text{sim}) = 110 \text{ mm}^{-1}$ [7], and measurements [10–12] at low gas pressure and with few millimeter gap widths when applying Paschen’s law to estimate the electric field strength under atmospheric pressure.

3.3 Time resolution

The timing behavior of the RPC has been studied for two gas mixtures at different field strengths. For the C₂F₄H₂/SF₆/i-C₄H₁₀ (85%/10%/5%) gas mixture measurements from 70 to 105 kV/cm have been performed and an improvement of the time resolution at higher fields is shown in figure 8. For the mixture C₂F₄H₂/i-C₄H₁₀ (85%/15%) measurements from 70 to 90 kV/cm have been carried out. Due to the absence of isobutane, the maximum field strength was reduced, and a degradation of the time resolution at higher fields is observed, cf. figure 9. It is worth mentioning that without isobutane and at a field of 70 kV/cm, the resolution for all different primary charge sizes is comparable and amounts to $\sigma = 30 \text{ ps}$. 

Figure 7. Effective Townsend coefficient for the gas mixture C₂F₄H₂/SF₆/i-C₄H₁₀ (85%/10%/5%) at 100 kV/cm. The red line shows an exponential fit, while the dashed line is a linear fit to the data.

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\caption{Effective Townsend coefficient for the gas mixture C₂F₄H₂/SF₆/i-C₄H₁₀ (85%/10%/5%) at 100 kV/cm. The red line shows an exponential fit, while the dashed line is a linear fit to the data.}
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Figure 8. Time resolution in dependence on the electric field strength for the gas mixture C$_2$F$_4$H$_2$/SF$_6$/i-C$_4$H$_{10}$ (85%/10%/5%).

Figure 9. Time resolution in dependence on the electric field strength for the gas mixture C$_2$F$_4$H$_2$/i-C$_4$H$_{10}$ (85%/15%), i.e. without SF$_6$.

4 Summary

The laser test facility at HZDR described here is the first apparatus which allows systematic precision measurements of gas parameters in the strongest available homogeneous electric fields at atmospheric pressure. We demonstrated that a strongly focused laser beam can be transported into a sub-millimeter gap of parallel plates. The narrow beam waist allows to shift the micro-focus along the field direction within the homogeneous electric field. For the first time gas parameters
for the three-component gas mixture $C_2F_4H_2/SF_6/i-C_4H_{10}$ widely used in timing RPCs were presented. The derived effective Townsend coefficient is in disagreement with theoretical assumptions and with measurements at low gas pressure, while the measured electron drift velocity fits well to Magboltz calculations. Systematic tests of different gas mixtures considered for timing RPCs are foreseen. A main goal is the substitution of climate harmful fluorine components. An upgrade of the apparatus should provide automatic data collection. To study field-charge effects, the increase of the laser pulse repetition rate up to $10^5$ Hz and the creation of a second micro-focus are under consideration.

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