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Studies of alternative gases and wavelength shifters for optically read out MicroPattern Gaseous Detectors

Company Internship Report

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1 Introduction

Gaseous detectors allow the detection of ionising particle, and they are widely used in the particle physics experimentation. The invention of electronically read out gaseous detectors by Georges Charpak in 1968 revolutionized the use of detectors for tracking by using electrical signals with an increased granularity of readout channels. This invention lead to the creation of Gas Detectors Development group at CERN.

After the initial invention, they have been further developed into more sophisticated devices with higher spatial and time resolutions. Gaseous detectors are used in many large scale particle physics, including LHCb, COMPASS and TOTEM experiments at CERN. After many successful implementations of wire-based detectors, the exploitation of advanced structuring processes lead to the introduction of MicroPattern Gaseous Detectors which overcome many of limitations of Multiwired proportional chambers, including the exposure of fragile electrodes to high energy fields which are needed for reaching high enough gains to detect small ionization yields [1], [2].

The gaseous detectors are based on the process of gas ionization. An incoming particle ionizes gas, producing electrons and ions, which are separated with an applied electric field, inducing signal on the anode by the electrons and on the cathode by the ions. In addition to detecting electrons, also optical readout is possible, as also photons are produced in the ionization process due to spontaneous emission [2].

The aim of this study is to examine the optical readout of gaseous detectors and the gases used within them. Tetrafluoromethane (CF_4) is a common gas for optical readout setups due to its unique properties, that are presented later. However, it is a strong greenhouse gas. The focus is to study alternative gases and methodologies to replace the CF_4.

This study is divided into two parts. The the first part focuses on studying the transmission properties of potential alternative gases. The focus is on the UV wavelength range, as most noble gases scintillate in that wavelength range. The second part focuses on the spatial resolution of the detector, considering different amplification structures and gaps between the amplification structure and the solid wavelength shifter.

2 Theory

2.1 Ionization

Ionization is a process in which an incoming particle, a hadron or a photon for example, interacts with an atom or a molecule. During the interaction, the incident particle can transfer energy, potentially releasing an electron from the atom. When an electron is released from a neutral atom, it becomes positively charged. These positively charged atoms are called ions. As the ions and the electrons have opposite charges, they pull each other together. If there are no other forces applied to these carriers, they recombine, becoming a neutral atom again. The energy required for the ionization process is called ionization energy. The ionization energy depends on the properties of the has mixture, such as the density and the charge. The number of ionization per centimeter of fast, minimally ionizing particles for argon, which is the primary noble gas utilized in this project, in 293.15 K temperature and 101.325 kPa pressure is approximately 30/cm [3].

Electrons are not necessarily stripped from the outermost electron shell of an atom during the ionization process. An atom or an ion can remain excited after the ionization, if an electron from an inner shell is stripped, or excited from a lower electron shell to a higher one. As the electrons transition from the excited state back to the ground state, the excess energy is emitted as a photon. This process is called spontaneous emission, or scintillation. Scintillation photons are able to induce further ionization of atoms. The scintillation peak wavelength of argon is around 100-200 nm [4].

2.2 Gaseous detectors

Gaseous detectors exploit the ionization process in detecting incoming particles. They consist of a gas chamber and two electrodes on the different sides of the gas volume. An electric field is generated inside the gas chamber by applying a voltage difference between the electrodes. When a charged particle traverses the gas volume, it can ionize the gas atoms, as explained above. The electric field inside the volume gas volume pull these carriers to opposite directions, as the electrons are drifted towards the anode and the ions towards the cathode. The electrons produced in this initial ionizing process are called primary electrons. The gap between the electrodes, where the drift takes place, is called the drift region [2].

When the electrons reach the anode, they generate measurable current. However, the signal from a low number of electrons is usually lost in the noise of the reading anode. Therefore, the detection of particles, which generates low amount of primary electrons, typically need some type of amplification. in addition to electrons, also ions move inside the detector, affecting the electric fields. The ions have much larger mass compared to the electrons, and are therefore moving much slower within the detector. The moving ions can affect on the subsequent events inside the detector and making the electronic measurement of the electrons more difficult. Furthermore, the larger concentration of ions within the drift region

increases the probability of electrons and ions recombining [2].

In this project, a continuous gas flow within the gas volume was maintained to avoid impurities from accumulating in the detector. The accumulation of ions is not a relevant problem n this project, as the ions eventually reach the cathode and are neutralized.

2.3 Multiplier structures

Gaseous electron multipliers (GEMs) can be used to amplify the signal within the gaseous detector by generating more secondary electrons. During the acceleration of the electrons, they can collide with other atoms inducing further ionization, and generating secondary electrons. The number of secondary electrons depends on the magnitude of the electric field, as a larger electric field increases the size of the avalanche.

The structure of GEMs is composed of two layers of conductors made of copper, separated by a dielectric layer. The thickness of the structure is typically 70 μm. Small holes, typically 70 μm in diameter, are etched to the structure, allowing electrons to traverse through the GEM. The typical layout of a GEM is shown in figure 1.

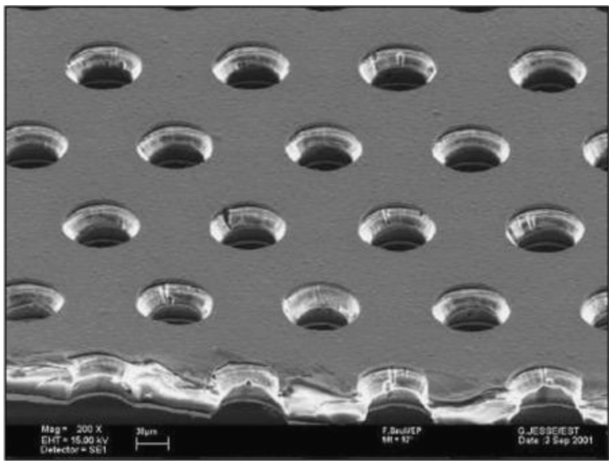

Figure 1: Typical structure of a gaseous electron multiplier foil [2].

When a voltage difference is applied across the conductor layers, the electric field within the holes increases significantly, as illustrated in figure 2. The electrons traverse through the holes due to the high electric field, and triggers an avalanche.

Another type of amplification structure used in this project is the Micro-Mesh Gaseous Structure (Micromegas). Micromegas is composed of a metallic mesh, typically a few micrometers thick. The mesh is separated from the anode by small insulating pillars, ensuring that the gap, called amplification gap, is constant across the entire surface. The thickness of the amplification gap is typically $50 - 70$ μm. When a voltage difference is applied between the mesh and the anode, an electric field is generated within the mesh and between the mesh and the cathode, as

shown in figure 3. A high electric field in this amplification region generates more secondary ionization, and therefore more electrons [5].

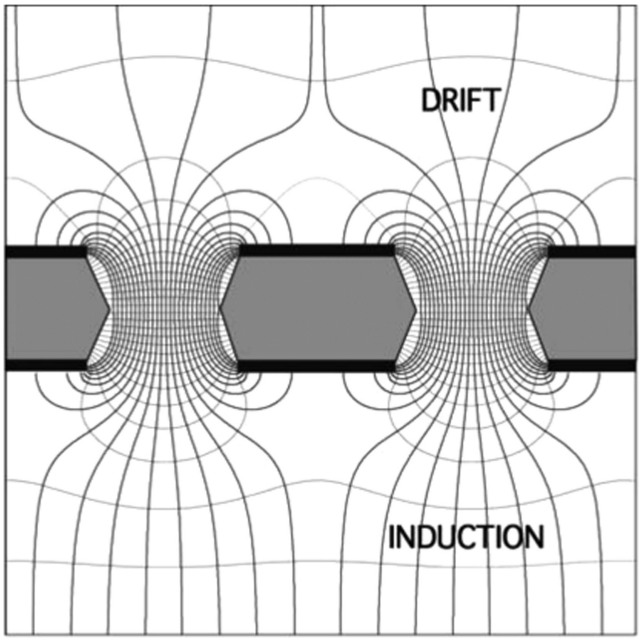

Figure 2: Electric field inside gaseous electron multiplier holes [2].

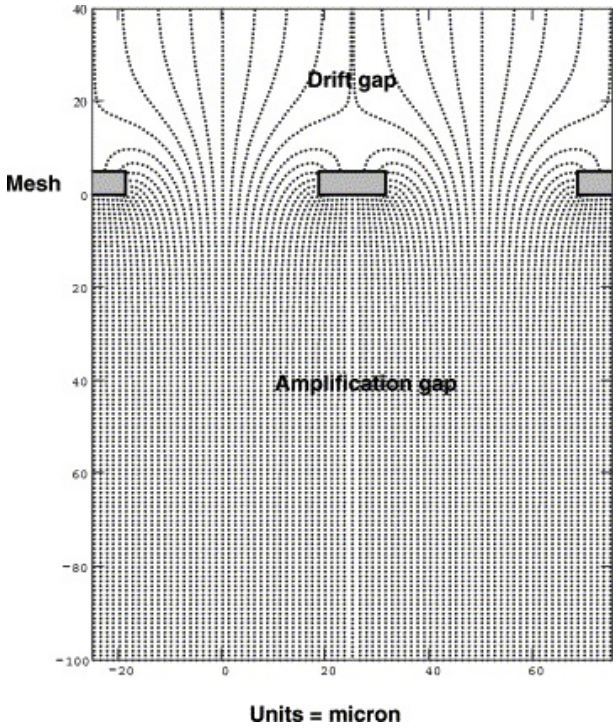

Figure 3: Electric field between micro-mesh gaseous structure and the anode [5].

2.4 Optical readout

As discussed in Section 2.1, scintillation photons are produced in the ionization process by de-excitations of gas atoms and molecules. Optical readout of gaseous detectors focuses on detecting these photons. There are two common ways to detect these photons: cameras and photomultiplier tubes.

Cameras offer a pixelated readout, which is an advantage when the path of the incoming particle is intricate, which would be significantly more challenging to reconstruct with electronic readout only. In addition, the magnification is easy with cameras by using different lenses. However, there are some limitations with the cameras, including a relatively low frame rate. In addition, commercially available charge-coupled device (CCD) and complementary metal-oxide-semiconductor (CMOS) cameras can only detect photons within the visible wavelength range.

In this context, CF_4 is a great scintillation gas due to its scintillation peak wavelength around 630 nm [3], enabling the usage of typical cameras for the detection. The scintillation spectrum of 20% CF_4 and 80% argon gas mixture is shown in figure 4. The intensity of the plot on y-axis is in arbitrary units, but it shows the shape of the spectrum. The two peaks, one in the visible wavelength range ($550 - 700$ nm) and the second in the ultraviolet wavelength range ($200 - 300$ nm), are scintillation light from CF_4. The scintillation light from argon is visible in the near infrared wavelengths, that is, the sharp peaks above 700 nm. The efficient wavelength range of a CCD camera is also visible in the figure (green curve), which aligns well with the CF_4 scintillation light peak. However, CF_4 is a really strong greenhouse gas which makes it more expensive and less available.

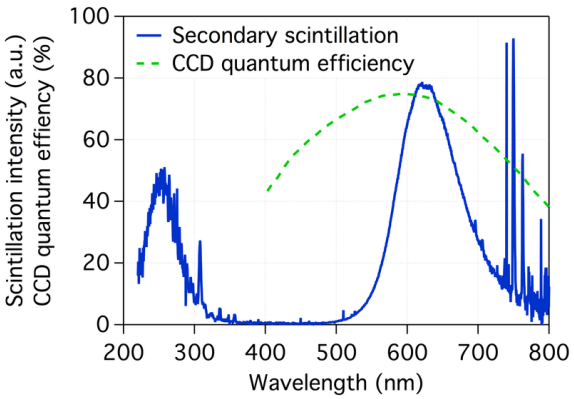

Figure 4: The scintillation spectrum of Ar/CF_4 80/20 gas mixture, and the quantum spectrum of a standard CCD camera [6]

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Instead of using some suitable scintillation gas, such as CF_4, solid wavelength shifters can be used, given that many noble gases scintillate in UV wavelength range. In this project, tetraphenyl butadiene (TPB) coated on the window was used for this purpose. TPB absorbs photons in 100-300 nm, and emits them around 430 nm, making it a suitable wavelength shifter for use with various noble gases, such as argon [3].

However, to mitigate potential issues, a quenching gas is needed to be mixed with argon. This arrangement prevents the photons from reaching the metal surfaces inside the detector, such as the cathode, and releasing an electron due to the photoelectric effect. This released electron induces an avalanche of ionizations, introducing instabilities into the detector [2].

In addition to cameras, photomultiplier tubes (PMTs) are used to detect small number of photons. When a photon enters the PMT, it strikes a photocathode, releasing photoelectrons from it. These electrons undergo acceleration within the vacuum chamber, driven by a focusing field generated by a cathode. Inside the PMT, there are multiple plates, called dynodes, each with different voltages compared to the cathode. When an electron collides with a dynode, multiple additional electrons are released by secondary electron emission, which are then accelerated toward the next dynode. This process repeats multiple times until the electrons are collected at the bottom anode. The PMTs can be efficient in UV, visible and near infrared wavelength ranges. In this project, PMTs are used in the transmission studies for measuring the intensity of transmitted UV photons through different gas mixtures [7].

3 Methods

The goal of this project is to study, if the CF_4 gas could be replaced in the gaseous detectors that are optically read out. The project is composed of two parts. In the first part, the focus is on examining the transmission properties of several gases in the UV wavelength range. The quenching gas needs to be transparent enough so that the scintillation photons of argon are able to transverse the gas, but still prevents them from releasing new electrons from the metal surfaces within the detector, creating instabilities. The goal is to determine if the argon and carbon dioxide gas mixture in some concentrations has similar transmission properties compared to the CF_4.

The second part of the project examines how the spatial resolution of the detector varies as the function of the gap size between the amplification structure and a solid wavelength shifter plate (TPB in this project). The motivation is that if a gas quenches the scintillation light from argon effectively enough to operate in stable conditions, a solid wavelength shifter plate becomes essential to shift the photons into visible wavelength range, so that they are detectable with cameras. The hypothesis is that if the gap between the amplification structure and the wavelength shifter plate is big, the resolution is worse, because the photons produced in the amplification region spreads more before they are absorbed in the TPB plate. This mechanism is illustrated in figure 5.

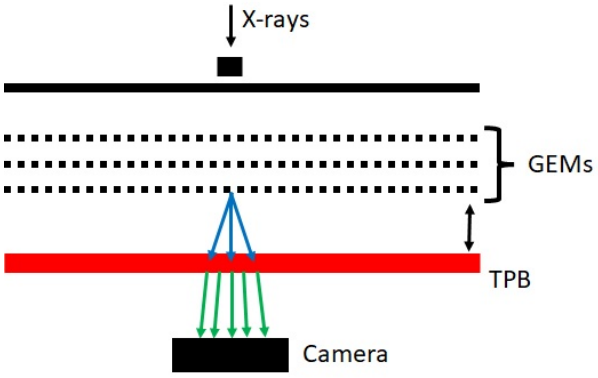

Figure 5: The photons produced in the amplification region spread in the gap between the amplification structure and the wavelength shifter plate.

3.1 Transmission studies

Transmission studies were conducted on pure carbon dioxide, pure argon and pure CF_4, as well as argon-carbon dioxide gas mixtures with following carbon dioxide concentrations: 30%, 7% and 2%. In addition, one type of hydrofluoroolefin (HFO) gas was tested. The setup included a vacuum chamber, a photon source, and a photomultiplier tube for the photon detection. The vacuum chamber is initially pumped down to a few 10^{-6} mbar pressure, and 9 reference value measurements for the light intensities are recorded at wavelengths ranging from 155 nm to 200

nm. After this, the gas mixture under study is pumped into the chamber at a pressure of 1 bar, and the light intensity measurements are repeated with the same wavelengths. The ratio of the transmitted intensity in the gas to that in the vacuum is calculated and plotted with respect to the corresponding wavelengths.

3.2 Spatial resolution studies

Spatial resolution measurements are conducted using two different measurement setups, both comprising an X-ray tube, a TPB plate and a camera. The amplification structure differed between the setups: one comprising three GEMs in a stack, and the other comprising Micromegas on top of a TPB plate. An image and an illustration of the setup is shown in figure 6. A small mask plate e.g. a linepair phantom is placed between the X-ray tube and the detector structure. Some of the light produced in the detector goes straight through the TPB, as it is semi-transparent, but ultraviolet light is absorbed and re-emitted in the visible wavelength range. After this, the photons traverse into the camera. The distance of the TPB plate from the last GEM was varied to determine how the spatial resolution changes as the function of the position of the TPB. The detector was opened every time the gap between the last GEM and the TPB was changed. Different gap thicknesses between the last GEM and the TPB were tested: 0, 0.5, 1, and 2 mm.

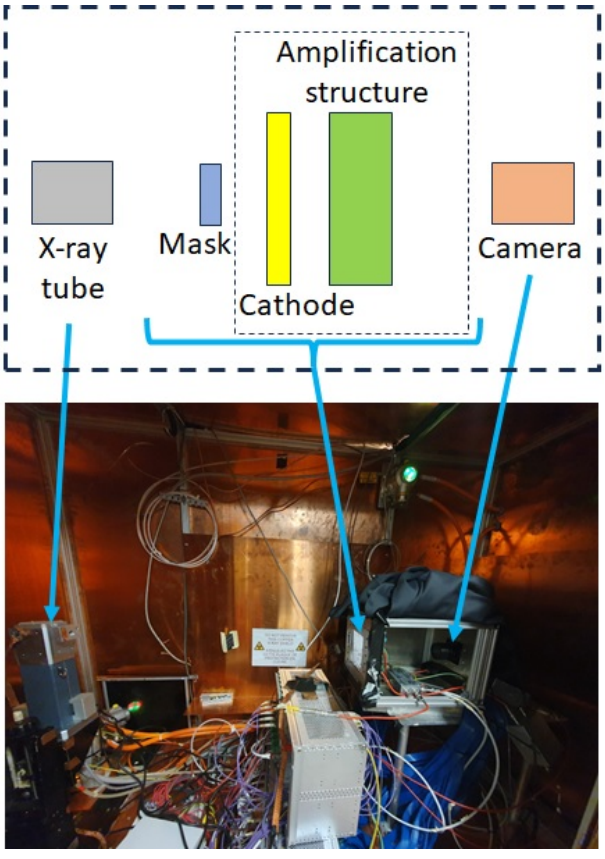

Figure 6: An image, and an illustration of the setup.

The energy of the photons from the X-ray tube were up to 20 kVwith the GEM setup and up to 30 kV with the Micromegas setup. The drift field for both setups was 1.25 kV/cm, the anode voltage of the Micromegas setup was 600 V, and with the GEM setups, the electrons were collected on the bottom of the last GEM, and a current of 3.15 μA was observed , which divided by the number of primary electrons corresponds to the gain of the detector. The gas used in these measurements were Ar/CF_4 80/20 and filters were used to get only light in the specific wavelength ranges. The scintillation spectrum of Ar/CF_4 80/20 gas is shown in figure 7, as well as the cutoff wavelengths of the short pass filter (SPF) and the long pass filter (LPF). The SPF cuts the light above 450 nm, which allows the detection of the emitted light from TPB. To see the scintillation light from the CF_4 gas without the TPB, the LPF is used to cut away the light below 510 nm.

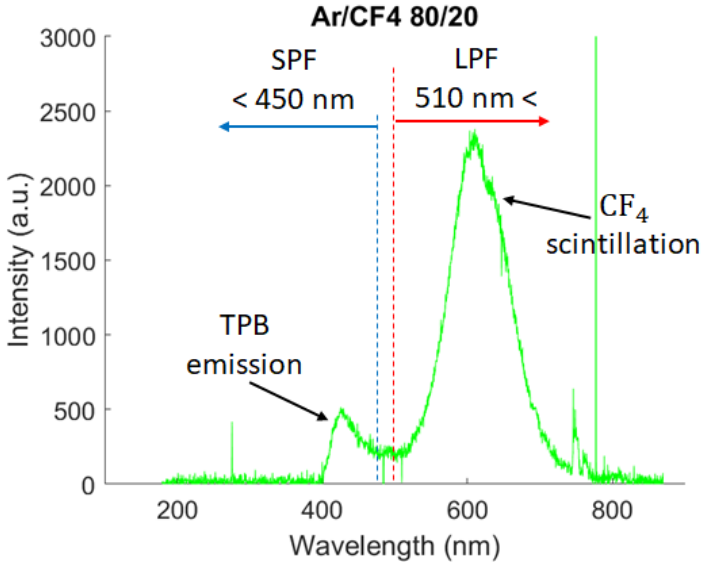

Figure 7: The scintillation spectrum of Ar/CF_4 80/20 with TPB, and the cutoff wavelengths of the SPF and the LPF visualized.

The exposure time on the camera was 60 seconds with the GEM setups and 120 seconds with the Micromegas setup. The process of quantifying the spatial resolution involves determining the distance needed for the transition from a white background to a darker object by focusing on a specific area on the side of the object, as shown in figure 8. Ideally the edge should be perfectly sharp. Any broadening of the transition from area with signal and background is ascribed to the imaging system and used to quantify the spatial resolution. The values of the pixels representing light intensity in the focus area is projected onto a profile plot. A fit is then applied to the plot using a function of the form

$$y_0 + \frac{A}{2}\mathrm{erf}\left(\frac{x - x_0}{\sqrt{2} \cdot s}\right),$$

where erf is the error function $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$. Free parameters are y_0, A,

x_0 and x, and s is the width of the fit, which is used as the quantity for the spatial resolution. The profile plot and the fitted function are illustrated in figure 9.

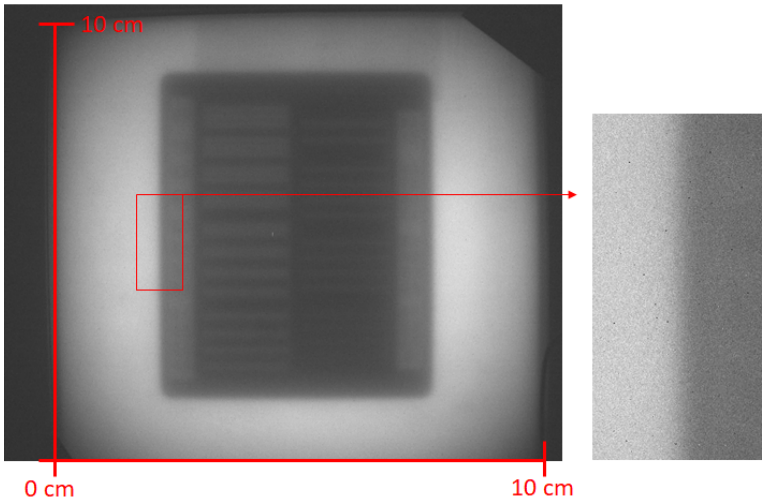

Figure 8: Example image of the plate. The red rectangle illustrates the area, from which the spatial resolution is determined.

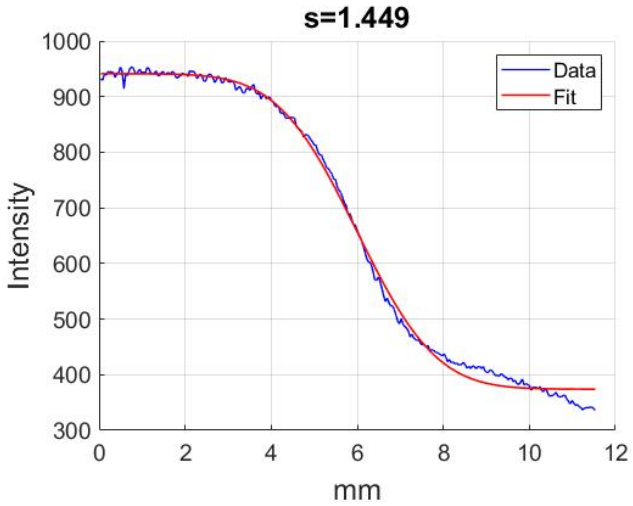

Figure 9: Profile of the example image area on the side plotted and the fitted error function.

4 Results

4.1 Transmission studies

The results of the measurements implies that the carbon dioxide quenches the light in the UV wavelength range much stronger than CF_4, even at concentrations as low as 2% when mixed with argon. The HFO gas guenches the light even more compared to the carbon dioxide. To allow the wavelength shifting from ultraviolet to visible wavelengths, the gas should be transparent for the argon scintillation light, that is, $100 - 200$ nm. The ratio of light transmitted through different gases compared to the light transmission in vacuum at different wavelengths is illustrated in figure 10. The vacuum transmission measurement (without any gas) was included in the figure to check the system, this should be 100% transparent. The transmission amplitude for CF_4 is also included as the reference. This result shows that carbon dioxide is not a viable alternative gas to CF_4 for optically read out detectors.

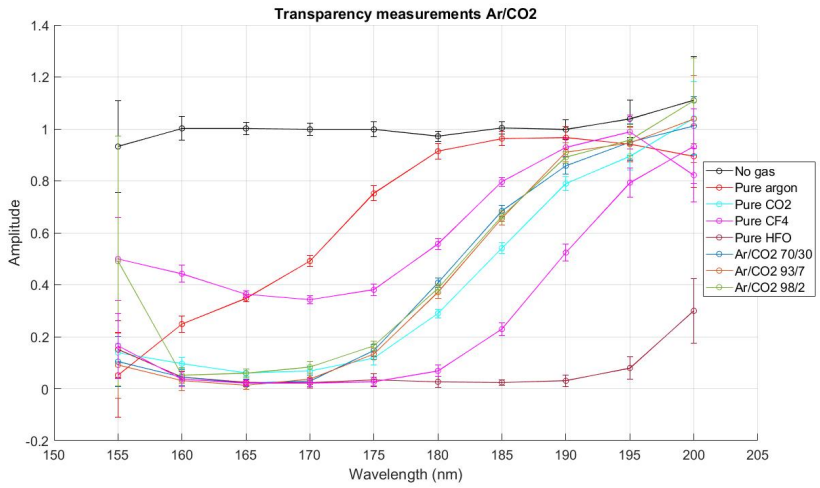

Figure 10: Amplitude of transmitted light in 150-200 nm wavelength range.

4.2 Spatial resolution studies

The best spatial resolution is obtained using the Micromegas amplification structure in direct contact with the TPB plate. The results of the measurements are illustrated in Table 1. The widths of the error function fits are presented in millimeters. The image of the setup is shown in figure 11. The resolution with LPF should remain the same between the measurements, but they varied a little. The measurements with SPF were as expected: the smaller the gap thickness between the multiplication structure and the TPB plate, the better the resolution. With the three GEM amplification setup, the best resolution is observed with a 0 mm gap, with the resolution of 0.465 mm (figure 12). The worst resolution is observed with a 2 mm gap with a resolution of 2.092 mm (figure 13). The MicroMegas on top of the TPB and GEM setup with 0 mm gap thickness were both stable. The

expectation was that some of the electrons would charge up the TPB plate and affect the stability, but this was not clearly observed. These results illustrate the effect of the placement of solid wavelength shifting planes on the obtainable spatial resolution.

		Width in mm	
	Gap in mm	**SPF**	**LPF**
Micromegas	0	0.209	-
3 GEM	0	0.465	0.333
	0.5	0.801	0.433
	1	1.433	0.520
	2	2.092	0.578

Table 1: Results of the spatial resolution studies. SPF stands for short pass filter, and LPF stands for long pass filter, respectively.

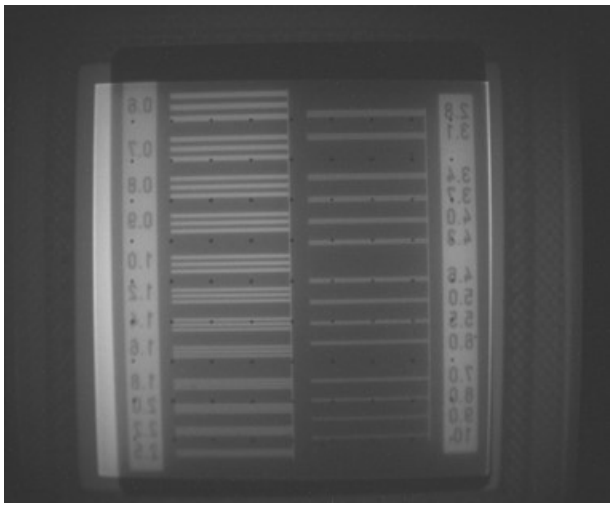

Figure 11: The image with Micromegas amplification structure and a short pass filter used on the camera.

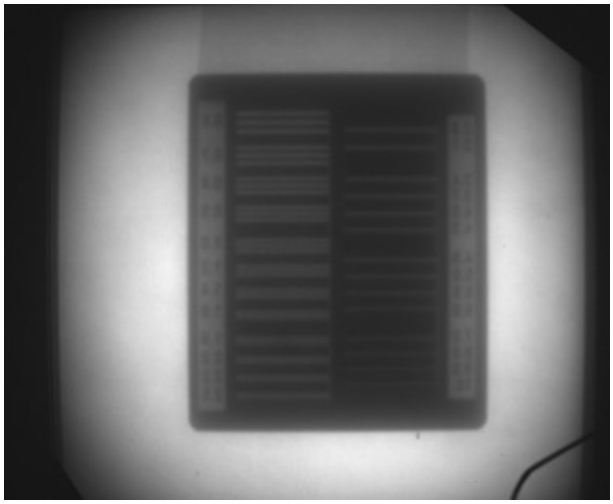

Figure 12: The image with three GEMs amplification structure, 0 mm gap between the amplification structure and the wavelength shifter, and a short pass filter used on the camera.

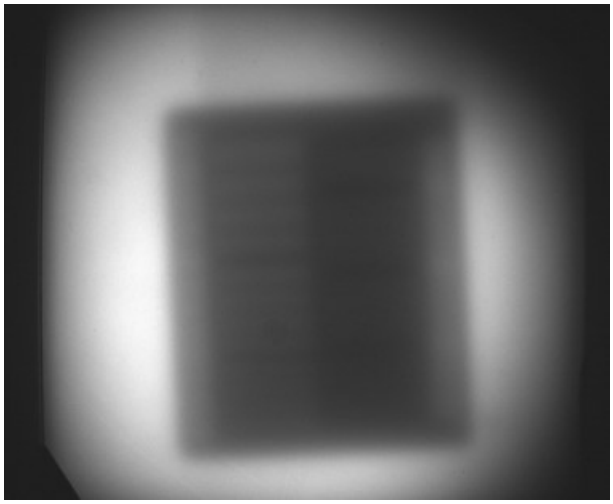

Figure 13: The image with three GEMs amplification structure, 2 mm gap between the amplification structure and the wavelength shifter, and a short pass filter used on the camera.

5 Conclusions

The results of this study shows that carbon dioxide (CO_2) has a stronger quenching effect on light in the 155-200 nm wavelength range compared to conventional tetrafluoromethane (CF_4). The measurements considered pure hydrofluoroolefin (HFO) gas, pure CO_2, as well as concentrations of 30%, 7%, and 2% of CO_2 in argon. Even with concentrations as low as 2%, CO_2 quenches the light in the 155-200 nm wavelength range much more effectively than 20% CF_4 in argon, which is commonly used as a quenching gas in gaseous detectors relying on optical readout. The quenching effect of HFO is even stronger compared to the CO_2. The objective of this study was to determine if CO_2 or HFO could be used as the quenching gas in optical readout setups instead of CF_4, as it is a strong greenhouse gas. The scintillation photons of argon should be able to traverse the gas mixture effectively enough to reach the photon detection structure, while being quenched enough to prevent instabilities in the detector.

The spatial resolution studies revealed that the gap size between the amplification structure and the wavelength shifter plate has a significant impact on the spatial resolution, with larger gaps leading to reduced resolution. The measurements were conducted using an Ar/CF_4 80/20 gas mixture in the detector, with gap sizes between the amplification structure and the wavelength shifter plate of 2 mm, 1 mm, 0.5 mm, and 0 mm. Two types of amplification structures were used: three Gas Electron Multipliers (GEM) in a row with all the aforementioned gaps, and Micro-Mesh Gaseous Structure (Micromegas) with only a 0 mm gap size. Micromegas structure has some advantages over the GEM structure in this setup, as the mesh structure is finer compared to the pith of the GEM holes, and the amplification region can be created directly on top of the wavelength shifter plate. A short pass filter, that cut away the light above 450 nm, was utilized to isolate the light from the TPB, as the scintillation peak of CF4 is approximately 630 nm, while the emission peak of the TPB is around 430 nm.

The objective of the spatial resolution studies was to determine how the variation of the gap between the last GEM and the Tetraphenyl Butadiene (TPB) plate induces changes in spatial resolution. The best spatial resolution was obtained using the Micromegas amplification structure in direct contact with the TPB plate, with a spatial resolution of 0.209 mm. With the three GEM amplification setup, the best resolution was observed with a 0 mm gap, with a spatial resolution of 0.465 mm, while the worst resolution was observed with a 2 mm gap, with a spatial resolution of 2.092 mm. These findings show that if an alternative gas with suitable transmission properties is found, a solid wavelength shifter plate is effective in shifting the scintillation photons of argon to visible wavelengths for detection with cameras with a good resolution.

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