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TECHNICAL REPORT

Investigation of UV laser ionisation in argon-based gas mixtures with a Triple-GEM detector

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ABSTRACT: In the gas detectors, the ionisation mechanisms of the charged particles and X-ray/γ-photons are well studied by theory and experiment. However, on the experimental measurements of the ionisation ability of the lasers, publications only give the estimation results. This study aims to fill the gap and measures the laser ionisation precisely. A GEM detector and an optical system have been set up to measure the laser ionisation. The purity of each component of the gas mixtures is indicated in this study. Our research shows that a pulsed laser with a wavelength of 266 nm can generate 100–200 electrons per centimeter, which equals to the ionisation produced by 1–2 Minimum Ionising Particles (MIPs) in argon-based mixtures. Furthermore, this study gives an experimental reference to select the laser energy density in argon-based gas mixtures when applying lasers to calibration in the gaseous detectors. We have also studied the impacts of different vendors and gas flow rates on the ionisation created by UV laser pulses.

KEYWORDS: Detector alignment and calibration methods (lasers, sources, particle-beams); Photon detectors for UV, visible and IR photons (gas); Time projection chambers

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2020 JINST 15 T02001

Contents

1 Introduction

TPCs (Time Projection Chambers) are widely used as the main tracking detector in high-energy physics experiments such as STAR [1] and ALICE [2] due to its excellent tracking efficiency and momentum resolution. The calibration of the distortion induced by electromagnetic field inhomogeneities in large TPC is always a critical task. For example, in CEPC (Circular Electron Positron Collider) TPC, the space charge created by ion back flow is expected to generate distortions on track reconstruction of the order of tens of microns [3]. These distortions severely deteriorate the TPC spatial resolution and need to be calibrated. The adoption of lasers provided a solution to the problem. Laser beams can simulate ionized tracks, by comparing positions of reconstructed tracks and pre-defined laser beams, distortions of tracks can be measured and calibrated. There have already been several experiments applying laser calibration systems. In ALEPH, the laser system is used to measure the drift velocity, $\omega\tau$ and the azimuthal coordinate shifts [4].The STAR TPC adopts a novel design to produce 252 laser beams uniformly distributed in each half of the TPC for calibration and has measured the drift velocity with 0.02% accuracy successfully [5]**.** A Nd:YAG laser, which wavelength is quadruped to 266 nm, is used in the experiment. The ALICE laser system follows the design of that of STAR and uses the same laser [2]. The diameter of the laser distributed in the chamber is 1 mm by intersecting the initial wide beams with many small mirrors.

In gas detectors, charged particles lose energy by ionisation and excitation of gases. As for UV lasers which wavelength is from 200 µm to 400 µm, the acknowledged interaction mechanism is a two-photon ionisation [6] process with organic impurities like phenol and toluene [7]. The ionisation potentials of gas molecules are much more than the photon energy of lasers, so they are not ionized by lasers. This mechanism has been quoted in many experiments applying laser ionisation to different gas detectors, and a rough laser ionisation density has been given. In STAR TPC, when the power density is adjusted to around 1 $\mu J/mm^2$, the ionisation density is equivalent to one MIP in P10 gas [8]. In ALICE TPC, because the gas mixture is the mixture of Ne-CO2-N2, to obtain the ionisation corresponding to several MIPs, the laser energy density should be increased to 40 μJ/mm^2 [2]. The average ionisation number of 115 is measured in an RPC using a N_2 pulsed laser (λ = 337 nm) [9]. As for the ionisation in the T2K gas, a typical value of 250 is acquired with a UV laser [10]. However, a clear relationship between the ionisation and laser energy density has been not observed yet.

The precise measurement of laser ionisation density is necessary. TPCs in different experiments may work in different conditions, such as gain, gas mixture, and pressure. If applying lasers in these experiments for calibration of TPC, one must ensure that laser signals are always in the dynamic range of the electronics to gain well-reconstructed tracks. In other words, under different situations, the laser energy density needs to be modulated to acquire appropriate ionisation density. Thus, an exact relationship between the laser ionisation density and energy density is required. This study presents a precise measurement of laser ionisation ability in different argon-based gas mixtures with a GEM (Gas Electron Multiplier) detector and examines several factors that may affect the laser ionisation ability.

2 Experimental setup

Gases mainly used in TPCs are studied in this experiment, including P10 gas ($Ar{:}CH_4$ = 90:10) [5], a mixture of argon and carbon dioxide ($Ar{:}CO_2$ = 90:10) and a fast gas mixture called T2K ($Ar{:}CF_4{:}iC_4H_{10}$ = 95:3:2) [11]. The purities of argon, carbon dioxide, methane, and carbon tetrafluoride is up to 99.999%, and the purity of isobutane is 99.9% as shown in table 1. Although the purity of isobutane is much lower than that of argon and carbon dioxide, the impurity concentration induced by isobutane should be in the same level with other gas compositions because there is only 2% isobutane in the gas mixture. In addition, the purer isobutane is unaffordable.

Table 1. Gas purities.

Gas	Purity
Ar	99.999%
CO_2	99.999%
CH_4	99.999%
CF_4	99.999%
Isobutane (iC_4H_{10})	99.999%

The layout of the detector and the optical system is shown in figure 1. The Nd:YAG laser generator is Q-smart 100 from Quantel Corp. with a frequency of 20 Hz, and a pulse duration of 5.64 ns. The wavelength is quadrupled to 266 nm. The diameter of the laser beam is 4.55 mm, and the beam divergence is 0.52 mrad. The laser pulse energy is adjustable, and the maximum is 20 mJ. In the optical system, the laser is first reflected by a (99/1) partially reflective mirror, which is used to attenuate the laser energy. Thus only 1 percent of the laser pulse energy is used. Then, the laser is collimated by two same diaphragms. Then, two diaphragms are used for beam collimating and narrowing the spot size of the laser beam down to 0.8 mm. A 3X beam expander which expands the spot size of the Gaussian laser beam to 2.4 mm is placed between diaphragms. The second diaphragm is used to select the laser beam with more uniform energy distribution. The diaphragm-expander-diaphragm structure further attenuates the pulse energy. In addition, an

2020 JINST 15 T02001

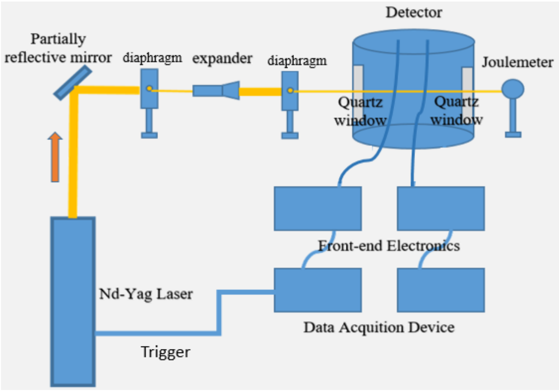

Figure 1. The layout of the experiment. The laser is attenuated by a partially reflective mirror and then collimated by two diaphragms.

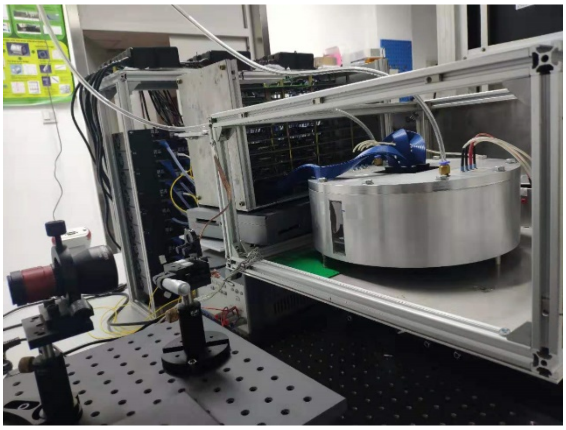

Figure 2. The Triple-GEM detector used in the experiment. There are two quartz windows with high transmittance introducing the laser into the chamber. The readout pads are on the upper part of the detector. Behind the detector is the front-end electronics.

expander can reduce the laser divergence angle. Finally, the laser enters the GEM detector through a quartz window. After exiting the chamber through another quartz window, the beam energy is measured by a laser energy meter (StarLite from Ophir corp.).

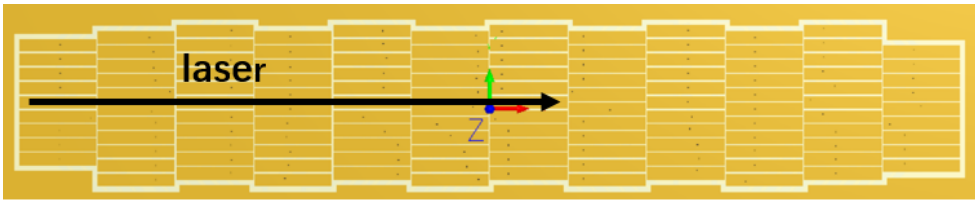

Figure 3. The structure of readout pads.

The Triple-GEM detector is shown in figure 2, with a drift length of 73 mm. There are two quartz windows on the detector for introducing the laser into the chamber. The electrons are multiplied in triple standard CERN GEMs [12]. The active area of the GEM is $100{\times}100\,\mathrm{mm}^2$, the pitch is 140 µm, and the outer hole size is 70 µm. The transfer gap is 1 mm thick, and the induction gap is 2.5 mm thick. The voltages are powered individually by a universal multichannel power supply system (CEAN SY5527). The drift field of the drift gap, transfer gapm and induction gap is 200 V/cm, 1000 V/cm, and 1000 V/cm separately. Electrons are collected by the readout pads that have 12 rows (128 pads in total, and each pad is connected with an electronic channel), shown in figure 3. The pad length is 6 mm, and its width is 1 mm. The front-end electronics is based on an ASIC named CASAGEM [13]. This ASIC was initially designed for the GEM-TPC. Each ASIC is integrated with 16-channel circuits, and the equivalent noise charge (ENC) of each channel is less than 2000. The gain and shaping time of the ASIC are adjustable, and they are set to 20 mV/ fC and 40 ns respectively during the experiment. The analog signals are then sent to a data acquisition (DAQ) system [14] and digitized by a 40 MHz clock.

2020 JINST 15 T02001

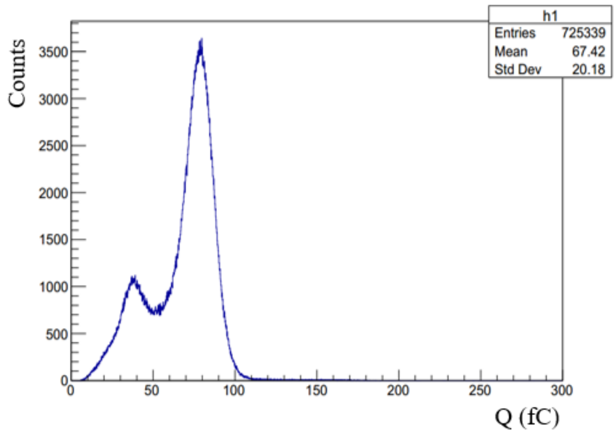

Figure 4. A ^{55}Fe spectrum measured in T2K gas. The sum of Triple-Gem voltage is 720 V. The gem detector works in triggerless mode. The timestamp is used to identify the event number. The event which has more than two fired pads is used to calculate the spectrum. The results indicated the detector gain is 2302.

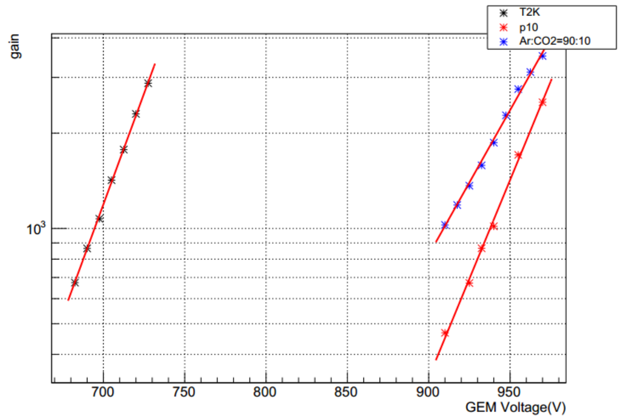

Figure 5. The detector gain curves of different gases obtained by ^{55}Fe source.

3 Results

3.1 The detector gain measurement

The 5.9 keV X-ray of a ^{55}Fe source that can produce approximately 221 initial electrons calculated by the W-value (the average energy per ionisation) of 26.4 eV for argon [15] in the GEM detector is used to measure the detector gain. A typical ^{55}Fe spectrum is shown in figure 4 with an escape peak (left) and a full-energy peak (right). The full-energy peak is used to compute the gain. Then, by changing the GEM bias voltage step by step, one can obtain the detector gain as a function of the bias voltage of GEM, as shown in figure 5. The gain will be used to estimate the laser ionisation.

3.2 The pulse height spectruam of the laser ionisation signal

The total energy deposition of laser in the chamber is obtained by summing charges collected by pads used in reconstructing the laser track for each laser incidence event. Only the events in which all pad rows have responses are chosen. The laser pulse height spectrum is shown in figure 6.

A Landau function is used to fit the distribution, and the MPV value represents the deposited charge. The concept of laser ionisation density is the number of primary electrons ionized by laser per centimeter. It is calculated by dividing the deposited charge in the chamber by the detector gain and the length of readout pad rows.

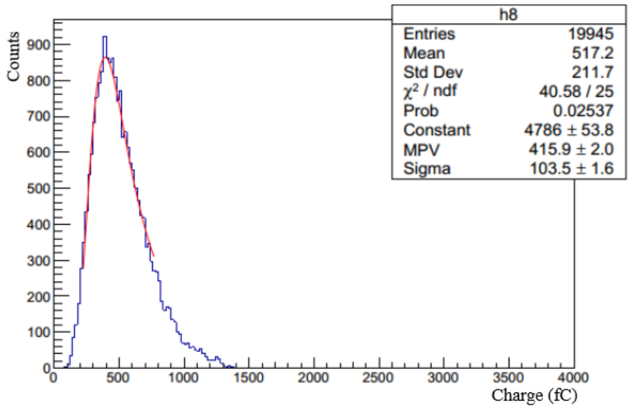

Figure 6. The pulse height spectrum of the laser ionisation signal measured in T2K gas mixture. The sum of Triple-Gem voltage is 705 V and the corresponding gain is 1407.

3.3 Laser ionisation density curves in different argon-based gases

The laser ionisation density curves in 3 different gases mentioned in section 2 (figure 7) are obtained by changing the incident laser energy density and measuring the corresponding ionisation density. The figure clearly shows a power law relation between the laser energy density and its ionisation density in all three gases. The power index is 3.04 for P10 gas (red line), 2.51 for the mixture of argon-carbon and dioxide (blue line), and 2.35 for T2K gas (red line). The figure shows that the laser ionisation density in P10 gas is significantly higher than that in the other two gases.

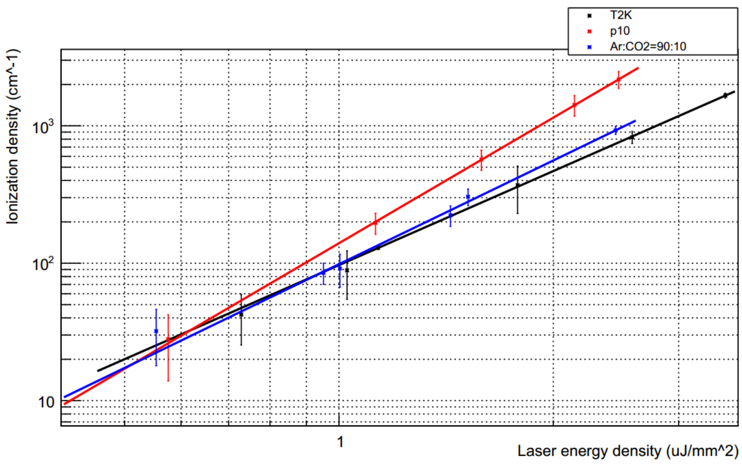

Figure 7. Laser ionisation density in different gas mixtures.

For calibration purposes, the laser ionisation should be similar to 1∼2 MIPs, which can generate 100∼200 electrons per centimeter in an argon-based gas. Our measurement indicates the incident laser energy density should be from about 1 μJ/mm^2 to 1.4 μJ/mm^2 for T2K gas and the mixture of (Ar:CO_2 = 90:10) and 0.9 μJ/mm^2 to 1.1 μJ/mm^2 for P10 gas.

3.4 The possible factors affecting laser ionisation

The crucial role of laser ionisation in gases is impurity concentration. Literature has shown that if the gas mixture was cleaned, the ionisation decreased significantly [11]. The first concern is that the impurity concentration in the same gas from different vendors differs, which may cause differences in laser ionisation. Thus, T2K gases with the same purity from 2 vendors are used to measure the laser ionisation density. Figure 8 shows that the two curves are similar. Especially in the area where the ionisation density is about 1–2 MIPs, the two curves almost overlap. The result verifies that the laser ionisation should be almost the same if gases from different vendors have the same purity.

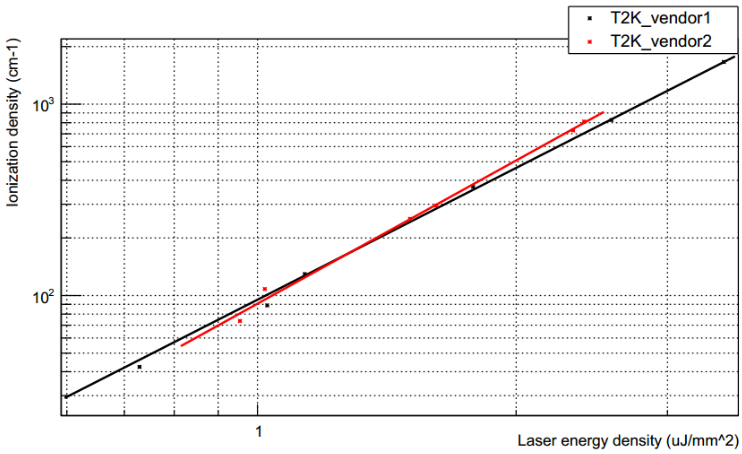

Figure 8. Laser ionisation density in the same kind of gas from different vendors.

TPC and GEM detectors generally work in gas circulation mode considering the gas consumption and pollution. So the second concern is if the gas flow rates may influence the impurity concentration and then affect the laser ionisation. Considering the volume of the chamber used is approximately 5300 ml, the gas flow rate is changed from 10 ml/min to 60 ml/min during the experiment, which is equivalent to 8.8 hours to 1.5 hours to fill the whole volume. Then, the corresponding laser ionisation density is measured. Figure 9 shows the result that the laser ionisation density has no correlation with the gas flow rate. It indicates that under our experimental conditions, the impurity concentration remains the same, or a small change of the impurity concentration does not influence laser ionisation.

4 Conclusions

A GEM detector is used to measure the laser ionisation density, which is a key parameter in the calibration of TPC using laser beams. The experiment indicates that an appropriate ionisation density (1~2 MIPs) can be obtained in argon-based gases that are widely used in TPC. The result gives a clear relationship between laser energy density and laser ionisation density which is an experimental reference to select the laser emergy density in argon-based gas mixtures when

2020 JINST 15 T02001

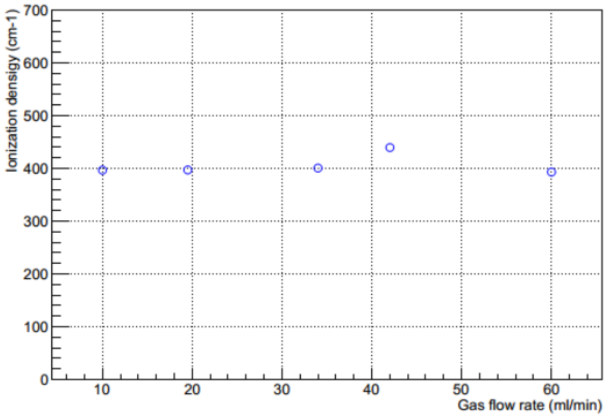

Figure 9. Laser ionisation density versus different gas flow rates.

applying lasers to calibration in the gas detectors. The factors that may affect the laser ionisation have also been examined. Experimentally, two conclusions can be drawn. First, for a certain gas mixture, if the purity of each component is the same, the laser ionisation density is the same, irrespective of production batches or vendors. Second, under our experimental conditions, the gas flow rate does not influence the laser ionisation.

However, there are still two items to be addressed. One is that the impact of gas pressure on laser ionisation is unclear. The other is that the laser energy deposition is found to obey a Landau distribution approximately in our experiment. While in previous research, it was found to be a Poisson distribution [6]. Further study is needed.

Acknowledgments

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2020 JINST 15 T02001