Investigation of the Avalanche Fluctuations Factor in Time Projection Chamber Detector Using 266 nm UV Laser

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Abstract

Time Projection Chambers (TPCs) are extensively used in collider experiments due to their superior physical performance. Particularly for future positron-electron colliders in Higgs physics studies, the next-generation TPC technology must provide better momentum resolution and improved spatial resolution. The avalanche fluctuation factor, a crucial parameter affecting spatial resolution, is challenging to measure accurately, whether directly or indirectly. This research leveraged the exceptional stability and ionization properties of ultraviolet lasers to achieve a precise determination of the avalanche fluctuation factor. The test outcomes were found to agree with the calculated values at the same gain levels, thereby validating the reliability of the experimental findings.

Full Text

Preamble

Investigation of the Avalanche Fluctuations Factor in Time Projection Chamber Detector Using 266 nm UV Laser

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Time Projection Chambers (TPCs) are extensively used in collider experiments due to their superior physical performance. For future positron-electron colliders dedicated to Higgs physics studies, next-generation TPC technology must deliver improved momentum and spatial resolution. The avalanche fluctuation factor, a crucial parameter affecting spatial resolution, is notoriously difficult to measure accurately through either direct or indirect methods. This research leverages the exceptional stability and ionization properties of ultraviolet lasers to achieve precise determination of the avalanche fluctuation factor. Our experimental results agree with calculated values at equivalent gain levels, thereby validating the reliability of our findings.

Keywords: Time Projection Chamber, UV laser, Avalanche fluctuation, Gas gain

Introduction

The Time Projection Chamber (TPC) [**?**] is a gas detector renowned for its high-precision measurement of particle momentum and position, capabilities that are essential for accurate particle identification. These attributes have made TPCs indispensable in particle physics experiments, as well as in low-energy nuclear physics and double beta decay studies [**?**, **?**, **?**]. The TPC has recently been confirmed as the baseline main tracking detector in the CEPC Reference Technical Design Report (refTDR) [**?**, **?**], and the International Linear Collider (ILC) also intends to adopt the TPC as its primary tracking detector [**?**].

For Higgs physics research at future positron-electron colliders [**?**], the next-generation TPC is targeted to achieve a position resolution of approximately 100 µm for tracks several meters in length. This precision is essential for meeting the demands of accurate Higgs property measurements. TPC performance is heavily dependent on its position resolution, which underscores the importance of measuring and optimizing the parameters that influence this resolution. These parameters are detailed in Eq. (1):

$$x = \sigma^2_{N_{eff}} = \frac{12}{N_{eff}} + \tan^2\phi$$

The term σ_0 represents the influence of factors such as electronic noise and electron amplification fluctuations on resolution. The second term accounts for the effect of drift and diffusion on position resolution, which is a primary determinant of overall performance. Here, D_T signifies the electron diffusion coefficient, N_{eff} represents the effective number of electrons, and z is the drift distance. The third term addresses the impact of track angles and pad size on position resolution, with the latter being constrained by N_{eff}. Position resolution is influenced by numerous parameters, making it a pivotal consideration in TPC design and optimization [?].

The parameters in Eq. (1) can be refined through research on Micro Pattern Gas Detectors, such as GEM [?] and Micromegas [?]. For the CEPC-TPC design, the T2K gas mixture (Ar:CF4:iC4H10 = 95:3:2) has been selected as the working gas. This mixture offers a reduced transverse diffusion coefficient D_T of approximately 43 µm/$\sqrt{cm}$ under conditions of a 2T magnetic field and electric field strength of 200 V/cm, allowing acceptable resolution degradation even at the maximum drift distance of 290 cm (half the length of the CEPC-TPC). However, precisely determining the critical parameter N_{eff} during the initial detector design phase is challenging due to the difficulty in accurately measuring the avalanche fluctuations factor f, whether directly or indirectly.

The effective number of electrons, N_{eff}, is defined by Eq. (2):

$$N_{eff} = \frac{(1+f)\langle N\rangle^2}{\langle N^2\rangle}$$

where N is the average primary ionization count and $f = \frac{\sigma_G^2}{\langle G\rangle^2}$ denotes the avalanche fluctuations factor. As factor f increases, gain stability deteriorates, degrading the detector' s position resolution [?].

In GEM detectors, factor f represents gain stability uncertainty arising from fluctuations near the micropores, as shown in Fig. 1(a). Stable gain corresponds to a higher N_{eff} value, ensuring that the induced charge on each pad accurately reflects the primary ionization distribution, thereby yielding precise positional data. In contrast, when gain stability is compromised (as illustrated in the lower portion of Fig. 1(b)), the charge distribution on each pad significantly diverges from the primary ionization. This divergence results in a diminished N_{eff} value and consequent degradation in the precision of position information derived from the center-of-gravity method. Consequently, precise experimental determination of the avalanche fluctuations factor is crucial for optimizing detector performance and enhancing overall precision.

Experimental studies often analyze the gas amplification charge spectrum generated by single photoelectrons from cathode materials, typically facilitated by illuminating materials with LED lamps or lasers to assess avalanche fluctuations. The Micromegas research group at CERN-RD51 measured factor f using a single-electron approach, achieving $f \sim 0.6$ in an Ar:iC4H10 = 95:5 gas mixture [?]. However, this method is challenging due to electronic noise interference, particularly at low gas gains, which complicates measurements and increases errors during extended acquisition times. Concurrently, the PandaX collaboration is exploring factor f using a liquid Xenon TPC [?, ?].

Factor f can also be estimated through simulation using empirical formulas, specifically Eq. (3) and Eq. (4):

$$P(G) = C_0 \frac{(1+\theta)^{1+\theta}}{\Gamma(1+\theta)} \left(\frac{G}{\langle G\rangle}\right)^{\theta} \exp\left(-(1+\theta)\frac{G}{\langle G\rangle}\right)$$

where C_0 is a constant, $\langle G\rangle$ represents the mean gain of the single-electron amplification distribution, and θ is a parameter determining the variance of the Polya distribution [?], related to the proportion of electrons with energy exceeding the threshold. The relationship between θ and f is expressed as:

$$f = \frac{1}{1+\theta}$$

We utilized COMSOL Multiphysics simulation software [?] to model the GEM microstructure, which was then imported into Garfield++ [?] to simulate gain in T2K gas, as depicted in Fig. 2. To align simulation settings with experimental conditions, we simulated the electron distribution after traversal through three layers of GEM amplification. By fitting the results with Eq. (3), we obtained values for C_0, $\langle G\rangle$, and θ, enabling estimation of f using Eq. (4). Simulation outcomes indicate that $f \approx 0.66$ at a gain of 1089 in T2K gas.

In recent years, our research has focused on experiments involving a 266 nm UV laser [?], using its ionization properties to assess factor f. This method leverages ionization tracks produced by the UV laser, providing a direct testing approach that minimizes data acquisition time. Furthermore, the laser' s exceptional monochromaticity and high stability contribute to uniform ionization clusters along the tracks, enhancing measurement precision. This paper elucidates the principles and setup of our testing methodology and presents measurement outcomes for factor f.

II. Stability Testing and Principles of UV Laser Operation

A. Application Mechanisms and Laser Selection

The ionization potentials of gases frequently employed in TPCs—such as argon (Ar, 15.7 eV), carbon dioxide (CO_2, 14.4 eV), and methane (CH_4, 13.1 eV)—are considerably higher than the photon energy of ultraviolet lasers. Consequently, these lasers cannot ionize the working gas through the photoelectric effect. For example, the photon energy emitted by an N_2 laser with a wavelength of 377 nm is approximately 3.68 eV, while that from a Nd:YAG laser at 266 nm is about 4.68 eV. However, research by Towrie et al. [?] has established that UV lasers can induce ionization of organic impurity gases present in the working gas. These impurities, with their complex energy level structures, primarily undergo two-photon ionization when interacting with UV lasers [?]. Consequently, advanced laser systems have been developed for STAR-TPC [?] and ALICE-TPC [?] to measure and monitor detector performance by creating uniformly distributed laser tracks throughout the detector system [?].

In our experiment, we utilized the Q-smart 100 Nd:YAG laser by Quantel, operating at a wavelength of 266 nm. The laser beam had a diameter of 5 mm and a beam divergence of approximately 0.3 mrad. The signal amplitude of the readout circuit is directly proportional to the laser energy and beam size. Gas ionization can be achieved using a UV laser with specific parameters: a gain of 5000, a spot area of 1 mm^2, a 2 mm readout strip, and a preamplifier amplitude of 140 mV [**?**]. Therefore, for subsequent experiments, we selected a spot area of 1 mm^2 and laser energy of 1-2 $\mu J/mm^2$.

B. UV Laser Alignment Stability Testing

Temperature fluctuations and vibrations can disrupt beam alignment, causing drift or jitter. Quantitative testing is essential to evaluate laser beam alignment stability. We assessed alignment stability using a CCD camera, as illustrated in Fig. 3(a). S1 and S2 serve as the beam splitter and aperture, respectively, with an aperture size of 1 mm^2. During testing, the laser beam is split by S1, with the transmitted portion monitored by an energy meter while the reflected portion passes through aperture S2 to form a narrow beam. After traveling 40 cm, the beam is projected onto a screen and continuously captured by a synchronized CCD camera. Over 20 minutes, the camera records the geometric center coordinates of the spot and calculates their average and standard deviation to assess alignment accuracy.

Spot center fluctuation is represented by two Gaussian functions in the X and Y directions, as shown in Fig. 3(b), with standard deviations of approximately 3.02 µm in the X direction and 2.34 µm in the Y direction. This high stability level ensures precise measurement of the avalanche fluctuation factor.

C. UV Laser Energy Stability Testing

In practical applications, variations in total energy output are unavoidable, primarily due to temperature fluctuations affecting crystal performance and inherent variations in emitted radiative photons during laser operation. For Nd:YAG lasers utilizing frequency-doubling, temperature changes within the system can particularly impact the performance of the frequency-doubling crystal. Although the laser's internal cooling system can partially offset these effects, testing laser energy stability is crucial to ensure accurate assessments.

To satisfy experimental demands for microjoule-level laser energy, we tested the stability of the attenuated narrow-beam laser using the Ophir energy monitoring system. The testing period lasted 20 minutes, with results presented in Fig. 4. The test results indicate that the average energy of the low-energy laser after attenuation is 46.59 µJ, with energy stability better than 2.9%. This degree of energy stability meets the requirements for measuring the gain stability factor.

III. Avalanche Fluctuations Factor Testing

A. Measurement Principle

As shown in Eq. (2), the effective number of electrons N_{eff} depends on factor f and the average primary ionization count N. Employing a 266 nm wavelength laser that operates via a two-photon ionization mechanism, it is possible to generate over 10 million ionized electrons at an energy density of 10 µJ/mm^2. The laser' s precise monochromaticity and stability ensure consistent ionization cluster sizes, while its ionization capacity can be fine-tuned by adjusting energy levels to exceed those of minimum ionizing particles, thereby fulfilling electronic signal requirements. Consequently, with constant primary ionization, N_{eff} depends primarily on factor f.

Recent studies have demonstrated that the laser ionization energy spectrum adheres to a Gaussian distribution following energy calibration, aligning with the laser beam' s energy distribution. Factor f can be determined by comparing charge signals Q_1 and Q_2 collected by adjacent pad rows after amplification of ionized electrons from the laser. The theoretical foundations of this method are derived from the literature [**?**, **?**].

The total number of amplified electrons N collected by a pad row can be represented by Eq. (5):

$$N = \sum_{i=1}^{n} g_i = g_1 + g_2 + \cdots + g_n$$

where n is the total number of primary electrons generated within a pad row' s range by laser ionization, and g_i is the gain of the i-th electron. The average number and variance of amplified electrons are expressed in Eqs. (6) and (7), respectively:

$$\langle N \rangle = \langle n \rangle \cdot \langle g \rangle$$

$$\sigma_N^2 = \langle n \rangle \cdot \langle g \rangle^2 \cdot (1 + f)$$

The fluctuation in primary ionization is indicated by $\sigma_n^2/\langle n \rangle$, with $\langle n \rangle$ being the average number of primary electrons per laser shot on a pad row. Due to laser stability or drift, fluctuations occur in the measured $\langle n \rangle$, leading to the average $\langle\langle n \rangle\rangle$ over a single experiment' s duration, as shown in Eqs. (8) and (9):

$$\langle n \rangle \equiv \langle\langle n \rangle\rangle + \delta\langle n \rangle$$

$$N \equiv \langle\langle n \rangle\rangle + \delta\langle n \rangle + \delta n$$

The average of σ_N^2 during a single experiment can be calculated as Eq. (10):

$$\langle\sigma_N^2\rangle \equiv \langle(N-\langle\langle N\rangle\rangle)^2\rangle = \langle\langle n\rangle\rangle \cdot \langle g\rangle^2 \cdot (1+f) + \langle g\rangle^2 \cdot \langle(\delta\langle n\rangle)^2\rangle$$

Factor f can be obtained by calculating the variance of amplified electrons collected by two nearby pad rows during a single measurement, as expressed in Eq. (11):

$$\langle(N_1-N_2)^2\rangle = \langle((N_1-\langle\langle N\rangle\rangle)-(N_2-\langle\langle N\rangle\rangle))^2\rangle = 2\cdot\langle\langle n\rangle\rangle\cdot\langle g\rangle^2\cdot(1+f)$$

Assuming that ionization signals collected by two adjacent pad rows are equal, then $\langle N_1\rangle = \langle N_2\rangle = \langle N\rangle$, and the fluctuation in laser ionization is eliminated by measuring the charge difference received by nearby pad rows. It follows that:

$$1+f = \frac{\langle(N_1-N_2)^2\rangle}{\langle g\rangle^2\cdot\langle\langle n\rangle\rangle} = \frac{\langle(N_1-N_2)^2\rangle}{\langle\langle N\rangle\rangle^2} = \frac{\langle(Q_1-Q_2)^2\rangle}{\langle\langle Q\rangle\rangle^2}$$

Therefore, determining factor f requires quantifying two key deviations: the relative fluctuation in primary ionization, denoted as $\sigma_n^2/\langle n\rangle$, and the relative variance in charge collected by adjacent pad rows, represented by $\langle(Q_1-Q_2)^2\rangle$. Consequently, our experiments focus on precisely measuring these two critical parameters.

B. Experimental Setup

The experimental setup is depicted in Fig. 5(a). The laser beam is initially attenuated using a 99:1 beam splitter to reduce its energy. Following this, the beam traverses two apertures for collimation, with a beam expander situated between them to refine beam quality. After clearing the second aperture, the beam area is expanded to 1 mm^2 and steered into the detector through a quartz glass window, aligning perpendicular to the electric field direction, where an energy monitoring system scrutinizes it.

To ensure precise measurement of the laser track, readout pads are centrally positioned within the effective readout area. These pads, which collect electrons along the laser trajectory, consist of 12 rows (128 total pads), with each pad connected to an electronic channel, as depicted in Fig. 5(a). The pad dimensions are 6 mm in length and 1 mm in width. The front-end electronics are based on an ASIC named CASAGEM, originally designed for GEM-TPC [?]. Each ASIC incorporates 16-channel circuits with an equivalent noise charge (ENC) of less than 2000 electrons per channel. The ASIC gain and shaping time are adjustable and were set to 20 mV/fC and 40 ns, respectively, for this experiment. Subsequently, analog signals are transmitted to a data acquisition (DAQ) system and digitized by a 40 MHz clock [?].

IV. Results

Before commencing laser emission, it is essential to confirm proper operation of both the DAQ system and energy monitor. An external trigger signal synchronizes measurement of the laser ionization signal with simultaneous recording of the laser pulse energy. Each data acquisition session spans 40 minutes. To maintain alignment between the laser ionization signal and laser pulse energy, the laser is turned off before the end of the data collection period.

The experiment initially measured gain at various voltages across the drift, transfer, and collection regions, as illustrated in Fig. 6. At a total voltage differential of 660 V, the gain is 800, escalating to 7500 at 730 V. For subsequent experiments, a total voltage differential of 670 V was applied, resulting in a gain of 1040, which aligns with electronic signal amplitude requirements.

To determine factor f, we measured the two key parameters outlined in Eq. (12). The charge Q recorded by the electronics from the pad is directly proportional to N, and since $\langle N_1\rangle = \langle N_2\rangle = \langle N\rangle$, therefore $\langle Q_1 - Q_2\rangle = 0$. Consequently, $\langle (Q_1 - Q_2)^2\rangle$ represents the standard deviation of the distribution of charge differences between adjacent pads. The measurement of $\sigma_n^2/\langle n\rangle$ is derived from the average primary ionization of the laser on the pad row, as depicted in Fig. 7(a). The mean and standard deviation of the fitting result correspond to $\langle n\rangle$ and σ_n, respectively, with the relationship between Q and n converted through the detector gain. Regarding the second parameter, $\langle (Q_1 - Q_2)^2\rangle$, we performed a statistical calculation of the ratio of charge differences to average collected charge near the pad. The statistical outcomes were plotted into a histogram to determine the standard deviation of the fitted distribution.

A parameter P can be defined as:

$$P = \frac{Q_1 - Q_2}{\sqrt{\langle Q_1 - Q_2\rangle^2}}$$

Then, $\langle\langle n\rangle\rangle \cdot \langle (Q_1 - Q_2)^2\rangle / \langle\langle Q\rangle\rangle^2 = 0.65 \pm 0.047$.

The experimental findings revealed an avalanche fluctuation factor of 0.65 at a gain of approximately 1040, which closely aligns with the simulated result of 0.66 at the same gain, thereby confirming the reliability of our experimental procedure. This result is consistent with the KEK experiment conducted in 2017, which reported f values of 0.65 and 0.62 at gains of 1900 and 5800, respectively. Furthermore, the average number of primary ionization electrons on the pad row, as shown in Fig. 7(a), was determined to be $N = 266.1$. Employing Eq. (2), the number of effective electrons was estimated to be $N_{eff} = 160.8$. Consequently, adjusting the laser energy to modify N in subsequent experiments may yield a higher N_{eff}, which could enhance the position resolution of the laser in TPC applications.

V. Conclusion

This study utilized a Triple-GEM cascaded amplification structure to investigate the avalanche fluctuation factor f using UV laser ionization tracks. At a gain of 1040, we achieved $f = 0.65$, which agrees with testing conclusions from KEK. This method is simpler than traditional approaches, demands lower electronic noise, and exhibits higher repeatability. To ensure UV laser stability, we conducted tests on its pointing and energy stability. The results indicated that the energy stability of the attenuated low-energy narrow-beam laser is better than 2.9%. The laser alignment stability in the X and Y dimensions was measured at 3.02 μm and 2.34 μm, respectively. Furthermore, accurate measurement of the avalanche fluctuation factor enables estimation of the effective electron number N_{eff}. By adjusting the laser energy, a larger N_{eff} value can be achieved, thereby enhancing the laser' s ultra-high position resolution. Consequently, the laser shows considerable potential for high-precision TPC research.

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Note: Figure translations are in progress. See original paper for figures.