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Enhancing Particle Identification for Future Circular Collider Experiments using Cluster Counting Technique

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Particle identification is a critical and challenging task in high-energy physics experiments, particularly for future collider facilities such as FCC-ee and CEPC. The conventional dE/dx method is limited by significant uncertainties in total energy deposition, which constrain its particle separation capability. The cluster counting (dN/dx) technique, instead, exploits the Poisson nature of primary ionization, providing a statistically robust approach to infer particle mass. Simulation studies performed with Garfield++ and Geant4 demonstrated that dN/dx can achieve up to a factor of two improvement in resolution of dE/dx in helium-based drift chambers. This improvement, however, requires precise detection of electron peaks and identification of ionization clusters—tasks complicated by signal overlap in the time domain. In this work, advanced algorithms were developed to enable accurate identification of electron peaks and ionization clusters. These methods were validated using beam test data collected at CERN with several drift tubes operated with different helium gas mixtures. The analysis results and a comparative study of the resolutions achieved using dN/dx and dE/dx methods are presented and discussed.

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1. The cluster counting technique

In helium-based gas mixtures, individual ionization clusters extend over only a few nanoseconds, allowing their identification with fast waveform readout electronics. Counting the number of clusters per unit length (dN/dx) provides a powerful alternative to the traditional energy-loss method (dE/dx), offering up to a twofold improvement in particle identification resolution.

Analytical studies based on a parameterized Bethe–Bloch model [1] show that, for a 90% He – 10% iC_4H_{10} mixture, cluster counting achieves significantly higher separation power than the standard truncated-mean dE/dx approach, even when assuming an 80% cluster-counting efficiency. When combined with time-of-flight information, simulation results using DELPHES for the IDEA detector concept at FCC-ee demonstrate efficient K/π separation ($\geq 3\sigma$) up to momenta of about 30 GeV [2].

Detailed Garfield++ and Geant4 simulations [3] have been performed to investigate the capabilities of the cluster counting technique in a helium-based drift chamber [4] and to assess its impact on particle identification performance. The results confirm that cluster counting substantially enhances particle separation capability, although small discrepancies are observed between the predictions of Garfield++ and Geant4. Since experimental measurements of cluster densities in helium-based gases are still limited, dedicated beam tests and laboratory studies are being pursued to validate the technique and benchmark the simulation models.

2. Experimental Setup

The beam tests employed a fully integrated setup based on stacked square drift tubes operated with a regulated He–isobutane mixture and read out without preamplifiers. The tubes were biased via an HV supply and terminated with 330 Ω decoupling cards to match their characteristic impedance. A scintillator–SiPM coincidence trigger ensured clean event selection.

Signal digitization was performed using the Wave Dream Board (WDB) [5], which provided 12-bit sampling at 80 MSPS via DRS4 chips running in transparent mode. Trigger logic was implemented in the onboard FPGA, and data were acquired autonomously through Gigabit Ethernet. This configuration minimized material, avoided the need for external tracking or time-to-distance calibration, and enabled cluster counting directly in the time domain.

Multiple tube geometries, wire diameters, gas gains, and He–isobutane mixtures were tested. Beam campaigns were carried out at CERN SPS-H8 (2021–2022, 40–180 GeV/c muons) and PS-T10 (2023–2024, 2–10 GeV/c muons), covering both the Fermi plateau and relativistic rise regions. Together with earlier PSI measurements, these tests provide essential validation of the cluster-counting technique. Full technical details of the setup and electronics are reported in Ref. [1].

3. Results

3.1 Electron Peak Identification and Cluster Reconstruction

The analysis presented in this work relies on the Running Template Algorithm (RTA) to identify electron peaks in the digitized waveforms. The RTA method employs an electron pulse template,

derived from data and digitized at the sampling rate, which is scanned over the waveform within a defined search window. A peak is tagged whenever the normalized template matches the waveform with a correlation above a predefined threshold. After each detection, the corresponding pulse is subtracted and the search is repeated iteratively until no further peaks are found. An example of the RTA peak identification is shown in Fig. 1 (left).

Identified peaks are subsequently grouped into primary ionization clusters using a dedicated clusterization procedure. Peaks that are temporally contiguous and compatible with diffusion-induced spreading are combined into a single cluster, with the drift time and amplitude assigned from the highest-amplitude electron in the group. Figure 1 (right) illustrates an example of the reconstructed clusters. The measured cluster distribution is consistent with a Poisson process and agrees with the analytical calculations described in [1].

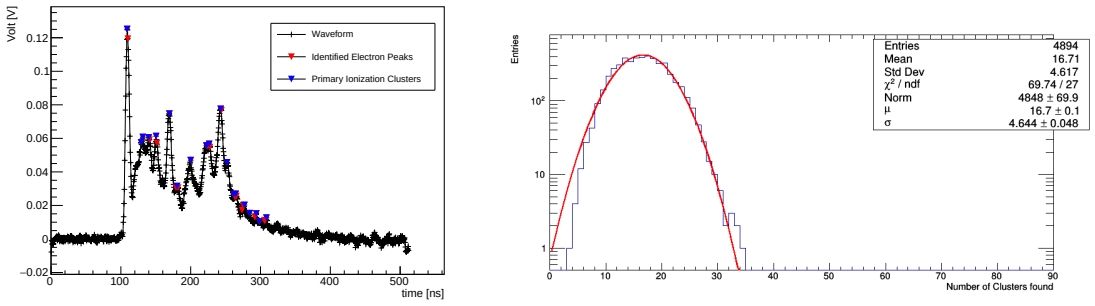

Figure 1: Recorded waveform from a 1 cm drift cell operated with a 20 μm sense wire, a 45° track angle, a 2 GSa/s sampling rate, and a He/iC_4H_{10} (90/10) gas mixture (left), and the corresponding distribution of the reconstructed number of ionization clusters using the RTA combined with the clusterization algorithm (right).

3.2 Comparison of dE/dx and dN/dx Resolution

A concise comparison of the energy-loss (dE/dx) and cluster-counting (dN/dx) resolutions has been performed using identical particle tracks reconstructed from hits in consecutive drift cells. The full methodology and reconstruction details are described in Ref. [1]. In the dE/dx method, the charge collected in each cell follows a Landau distribution, and a truncated mean—removing the highest-charge samples—is used to suppress large fluctuations from δ electrons.

The dN/dx resolution is obtained from the same tracks using the RTA + clusterization algorithm, described in Section 3.1, is applied to reconstruct the ionization clusters. Figure 2 shows the comparison between the truncated charge measurement and the number of reconstructed ionization clusters for an effective track length of about 2 m. The dN/dx technique achieves a resolution of 3.01 ± 0.20%, nearly twice as good as the 5.7 ± 0.39% obtained with dE/dx, in agreement with analytical expectations and simulation studies.

The dependence of the resolution on track length is summarized in Figure 3. The dE/dx resolution follows an $L^{-0.37}$ scaling, consistent with previous observations, while the dN/dx method exhibits an $L^{-0.5}$ behavior, reflecting the statistical advantage of counting independent ionization clusters. These results demonstrate the superior intrinsic resolution achievable with the cluster-counting technique.

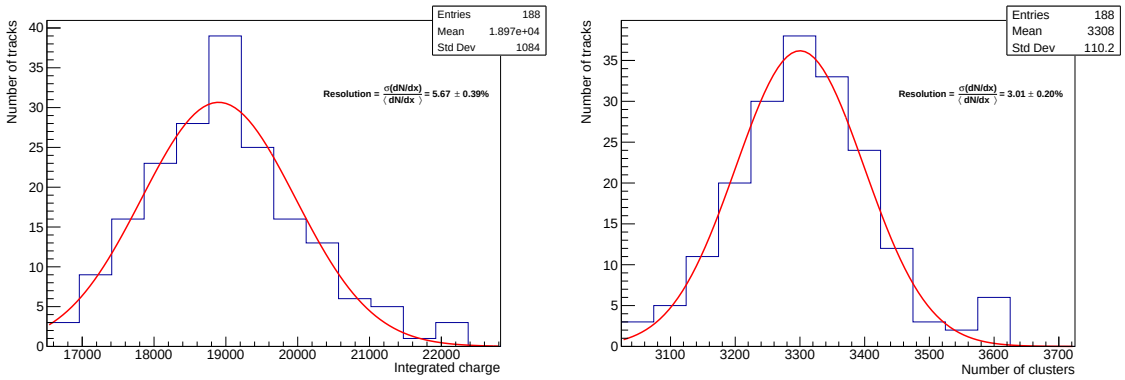

Figure 2: Integral of the truncated mean charge distribution at 80% (left) and the number of ionization clusters (right) measured along 2-meter tracks constructed from the same hits. The red curves represent the Gaussian fits to the data, with the quoted resolutions including the propagated fit uncertainties.

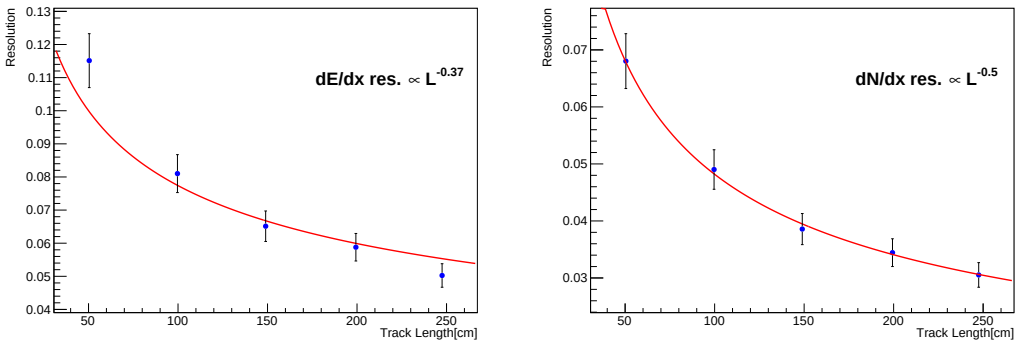

Figure 3: Resolution as a function of track length (L) for the dE/dx method (left) and the dN/dx method (right). The red lines represent the fits with power-law dependencies $L^{-0.37}$ for dE/dx and $L^{-0.5}$ for dN/dx. The corresponding fit qualities are $\chi^2/\text{NDF} = 1.56$ for dE/dx and $\chi^2/\text{NDF} = 0.04$ for dN/dx.

3.3 Improved dN/dx Resolution

Further improvements to the dN/dx resolution were achieved through waveform cleaning and a correction for time-dependent electron losses, with full methodological details available in Ref. [1]. The waveform cleaning removes distorted or anomalous signals by enforcing consistency criteria on cluster duration and rejecting tracks with wide or noisy waveforms. This procedure suppresses spurious clusters and improves reconstruction quality, yielding a resolution improvement from $3.01 \pm 0.20\%$ to $2.37 \pm 0.16\%$, as shown in Fig. 4 (left).

A second correction accounts for the loss of ionization electrons due to recombination and attachment during drift. A time-dependent factor is extracted from the correlation between the number of clusters and the drift time of the first cluster, and applied on an event-by-event basis. This procedure is performed separately for each detector configuration. The correction provides an additional improvement of the dN/dx resolution, from $2.37 \pm 0.16\%$ to $2.28 \pm 0.15\%$, as illustrated in Fig. 4 (right).

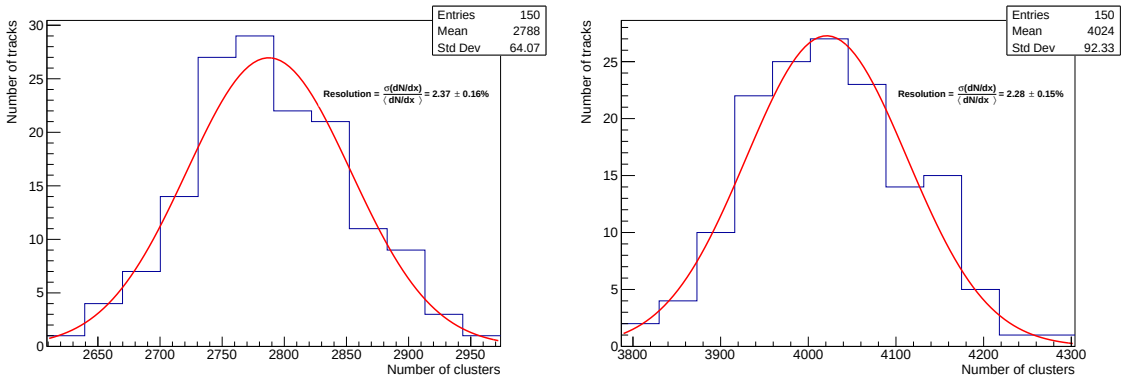

Figure 4: Number of ionization clusters measured along 2-meter tracks: after waveform cleaning (left), and after applying both waveform cleaning and recombination and attachment correction (right). The red curves represent the Gaussian fits to the data, with the quoted resolutions including the propagated fit uncertainties.

4. Conclusions

The cluster counting technique has demonstrated a clear advantage for particle identification, achieving significantly better resolution than the traditional $\mathrm{d}E/\mathrm{d}x$ method. Using the same reconstructed tracks, the baseline $\mathrm{d}N/\mathrm{d}x$ resolution is nearly twice as good as $\mathrm{d}E/\mathrm{d}x$, consistent with analytical expectations. Additional refinements—waveform cleaning and a time-dependent correction for recombination and attachment—further improve the $\mathrm{d}N/\mathrm{d}x$ resolution to $2.28 \pm 0.15\%$ for 2-m tracks. These results confirm the robustness of cluster counting and its strong potential for future high-precision PID applications. Continued analysis of the 2023–2024 beam tests will enable further optimization of the technique.

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