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Garfield++/LTSpice for modelling response of Straw Tubes with custom readout

Assel Mukhamejanova[1,2,3], Vitalii Bautin[1], Sophie Bulanova[4], Temur Enik[1], Ekaterina Kuznetsova[4], Yerzhan Mukhamejanov[1,2,3], Andrei Zelenov[4]

[1]Joint Institute of Nuclear Research [2]Al-Farabi Kazakh National University
[3]Institute of Nuclear Physics; [4]NRC Kurchatov Institute - PNPI;

E-mail: assel.mukhamejanova@cern.ch, vitalii.bautin@cern.ch, bulanova.sophie@gmail.com, temur.enik@cern.ch, ekaterina.kuznetsova@cern.ch, yerzhan.mukhamejanov@cern.ch, andrei.zelenov@cern.ch

Abstract. This study explores the modeling and prediction of the straw tube detector performance using Garfield++ and LTSpice. Straw Tube Trackers (STT) are important components in high-energy physics experiments because of their large detection area and low material cost, making them an attractive option. The aim is to accurately predict drift time and signal shape of straw response, which are crucial for optimizing readout electronics of future STTs.

The research involves integrating Garfield++, a simulation toolkit, with LTSpice, an electronic circuit emulator, to simulate detector responses comprehensively. The study validates simulation predictions with experimental measurements from VMM3 and Tiger ASICs, focusing on refining model accuracy. Key challenges include measuring signal timing and charge simultaneously to enhance detector performance.

This work advances the precision and reliability of particle detection systems, optimizing readout systems and improving straw tube detector performance. Ongoing efforts focus on developing new ASIC prototypes for future high-energy physics applications.

1. Introduction

Straw Tube Trackers are critical components in numerous current and forthcoming experimental setups. These trackers offer significant advantages, including a large detection area and minimal material budget. Notable examples of existing trackers include the ATLAS Transition Radiation Tracker (TRT) [1], which employs straw winding technology, and the NA62 tracker [2], which utilizes ultrasonic welding. Future trackers that will be constructed using straws produced by ultrasonic welding include those of the SPD experiment [3] at JINR, the DUNE experiment [4] in the United States, as well as the SHiP experiments at CERN, and the COMET experiment in Japan.

In straw trackers, the reconstruction of track coordinates is based on the measured signal arrival time, which is determined by the drift time of primary electrons from a particle track to the anode wire. During development and construction phases of a tracker, it is crucial to accurately predict its performance for specific geometries, gas mixtures, and readout electronics.

This work represents a continuation of the study presented in [5], where the performance of straw tube detectors was analyzed using Garfield++ simulations. Building upon the previous

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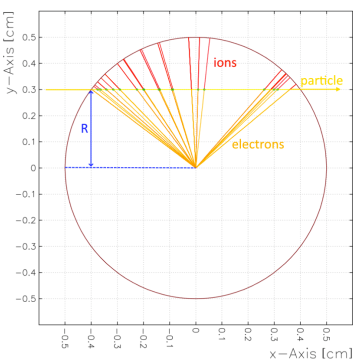
research, this paper expands the scope by incorporating additional factors such as use of two distinct front-end electronics configurations (VMM3 and Tiger ASICs) and explores their impact on timing and charge measurements. Additionally, the study refines simulation parameters to improve the accuracy of predictions and aligns them with experimental data.

Garfield++ [6] is an object-oriented toolkit designed for comprehensive simulation of signals in gaseous detectors. When interfaced with an electronic circuit emulation program such as LTSpice [7], it enables a complete simulation of the straw response as it would occur in a real experimental conditions. Garfield++ features a user-friendly interface for configuring simulations while providing extensive customization options for more precise modeling. Users are able to define particle interactions, detector materials, gases, electrical and magnetic fields. The toolkit incorporates robust libraries for cross-section calculations and particle tracking, ensuring an accurate representation of the mechanics of straw tubes.

2. Straw Tubes



Straws are gas-filled cylindrical tubes with a conductive inner layer as cathode and an anode wire stretched along the cylinder axis.

Charged particles traversing a straw ionize the gas. Electrons drift towards the anode wire. Charge amplification occurs in the high electric field near the anode. The signal is further amplified, shaped, and discriminated by read-out electronics. The discriminated signal marks the time which is needed for electrons from the primary ionization clusters closest to the anode, to reach it. This allows precise tracking when multiple straws are arranged in layers. This configuration forms a tracking detector capable of reconstructing particle trajectories with high precision.

3. Simultaneous Measurements of Signal Timing and Charge

Simultaneous precise measurements of signal timing and charge represent a significant challenge for straw tube readout. Existing Application-Specific Integrated Circuits (ASICs), such as the VMM3/3a [8] and Tiger [9], have been tested within the StrawTrackerRD experimental setup. However, these options do not provide a definitive solution for straw detector readout due to limitations such as inadequate timing resolution, insufficient charge measurement capabilities, and integration challenges within the overall detection system.

The goals of our study:

- to develop a procedure that can predict the performance of time and charge measurements for a given straw readout model
- to validate this procedure with experimental measurements done for straw tubes using VMM3 and Tiger ASICs. By comparing the predicted performance with the experimental data, we can assess the accuracy of our predictions and refine our modeling techniques.
- to predict the performance of readout systems which are under development. This predictive capability will facilitate the design and optimization of new ASIC prototypes, enabling faster iterations and improvements in future designs.

4. Simulation

This section explores the detailed analysis of signals simulated from straw tubes using Garfield++ and processed with LTSpice. The signals generated through Garfield++ simulations provide essential insights into the behavior of the straw tube detectors. Subsequently, these signals are processed using LTSpice, recognized for its excellence in electronic circuit analysis and design. LTSpice is renowned for its ease of use, widespread adoption, and free availability, combined with superior convergence properties that ensure highly accurate simulations.

The figure on this section illustrates two key components: Figure 1 presents an example of a signal from a straw tube as simulated by Garfield++ and Figure 2 shows overlay of the original Garfield++ signal and the corresponding signals processed by LTSpice.

These processed signals serve as a foundation for further analysis, enabling to conduct a comprehensive evaluation of electronic behavior in straw tube readout systems. This analysis is pivotal for optimizing readout component values, refining circuit configurations, and ultimately enhancing the effectiveness of particle detection technologies.

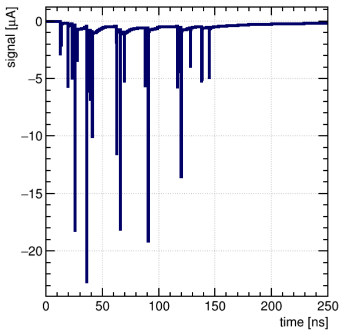


Figure 1. Signal from a straw tube simulated by Garfield++

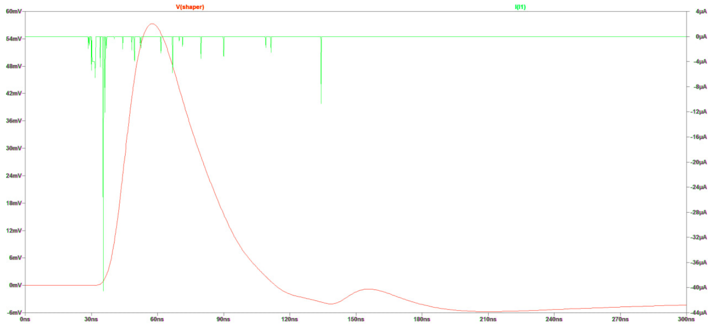


Figure 2. LTSpice response (red) to a signal provided by Garfield++(green)

4.1. Detailed Simulation Analysis Parameters

The simulation studies were performed for the following parameters:

- Straw tube diameter: 10 mm
- Anode wire diameter: 30 μm
- Applied high voltage: 1750 V
- Gas mixture: 70%Ar + 30%CO_2
- Operating temperature: 20 °C
- Gas pressure: 1 atm
- Ionizing particle: 1 GeV muon
- Electronic models used: VMM3 and Tiger ASICs in LTSpice
- Noise level: ENC of $1500e^-$ for VMM3 and $2000e^-$ for Tiger

4.2. Signal Visualization and Distribution

Figure 3 and Figure 4 show the signals after being processed through two versions of LTSpice modeling: VMM3 and Tiger. Through this comparison, our objective was to select the ASIC version that best meets our performance criteria and experimental requirements. High gain of the Tiger ASIC makes it saturated with a typical straw signal, though still alow to provide time measurement.

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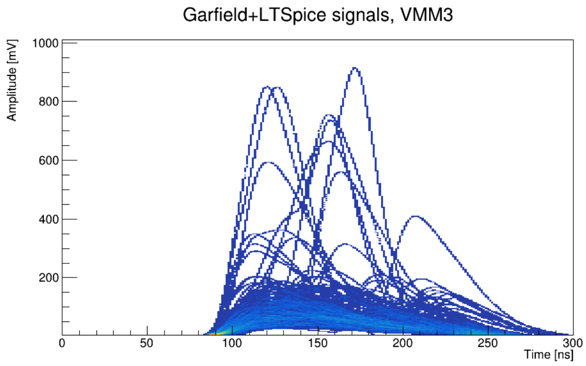


Figure 3. Garfield++/LTSpice signals, VMM3

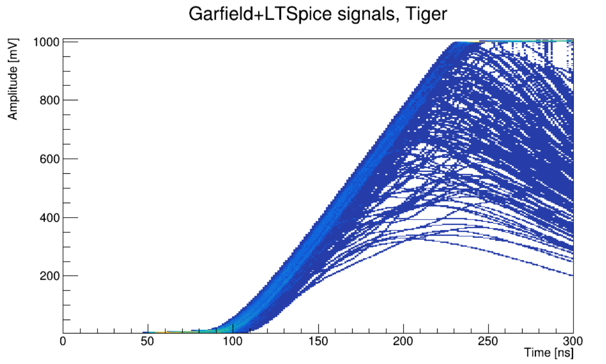


Figure 4. Garfield++/LTSpice signals, Tiger

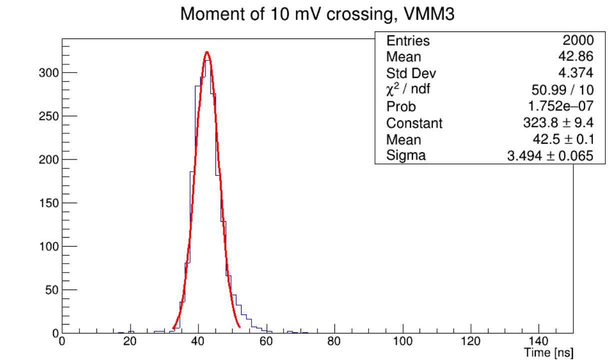


Figure 5. Moment of 10mV crossing, 2mm from anode, VMM3

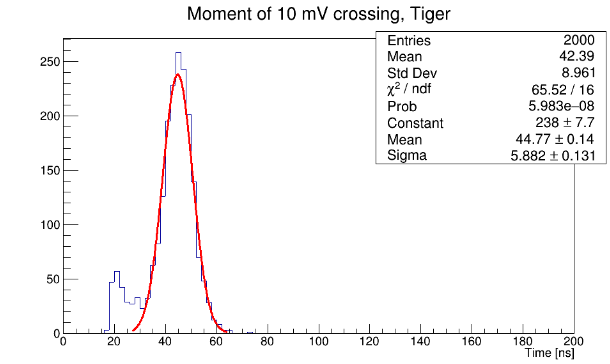
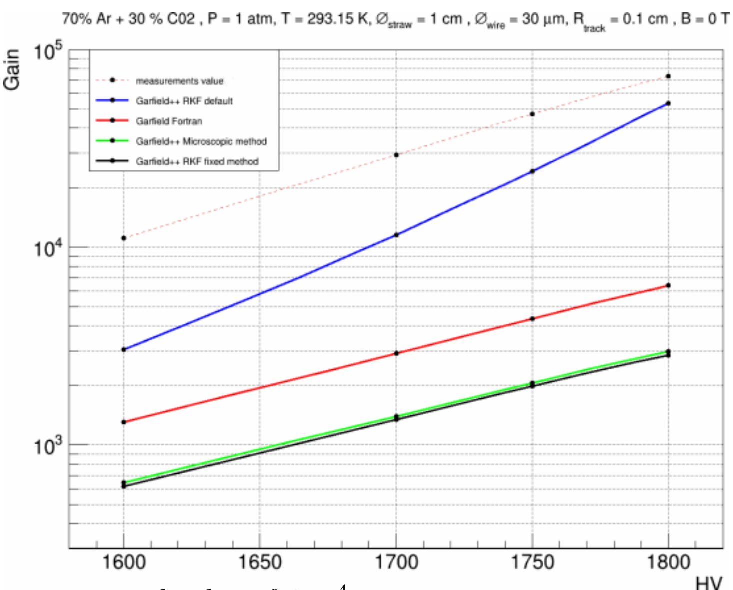


Figure 6. Moment of 10mV crossing, 2mm from anode, Tiger

4.3. Gas gain prediction



In our study, we encountered challenges in reproducing measured values [10] of charge in an avalanche originating from a single electron (gas gain) for a 10 mm straw tube. We compared several methods: the old Garfield(Fortran) simulation, the Runge-Kutta-Fehlberg method, and microscopic methods, all using a Penning transfer coefficient of 0.54 to experimental data. The Runge-Kutta-Fehlberg method, when adjusted to match the average gain predicted by the microscopic method, successfully reproduced the values obtained from the microscopic approach. However, none of the methods reproduced the experimental value of $4.5e^4$.

Currently, as a temporary solution, we set the Penning transfer coefficient to zero and fix the gas gain using the Polya function within the Runge-Kutta-Fehlberg method to represent the experimental data. We acknowledge existing discrepancies and plan to resume investigations to resolve these issues soon.

This approach allows us to maintain consistency with experimental observations while we continue to refine our simulation models to better align with empirical data.

4.4. Evaluation of Gas Gain Adjustments

In this section, we assess the effectiveness of our temporary solution for gas gain adjustments. We focus on plotting the total charge generated from a single electron and examining the ratio of the total charge to the number of primary electrons for a muon track. This analysis is conducted across various distances from the anode wire to ensure comprehensive evaluation. Figure 7 shows the number of electrons in a single avalanche. We utilize the Polya function to determine the number of total electrons produced per single primary electron. This metric provides insight into the amplification process and its variability. Figure 8 shows the total charge divided by the charge of all primary ionization clusters for a muon track. This ratio is crucial for understanding the efficiency and consistency of charge collection in the straw tube detector.

Analyzing these parameters, we aim to validate our quick fix approach and ensure it aligns with the expected performance metrics. This evaluation is essential for refining our simulation models and improving the accuracy of our predictions regarding straw tube detector performance.

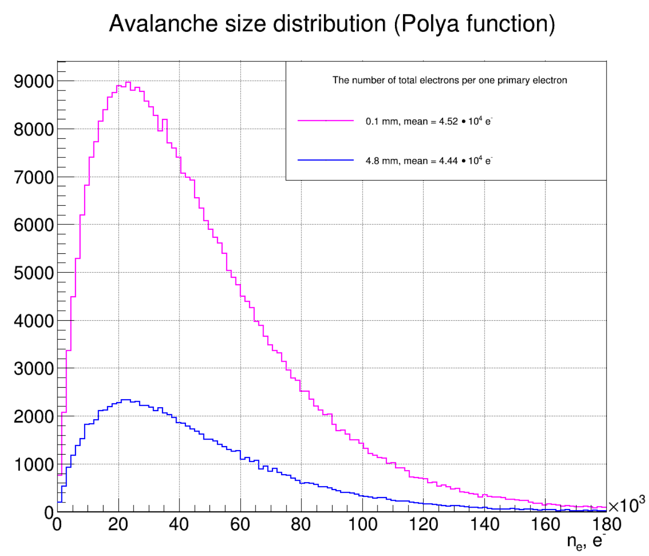


Figure 7. The number of electrons after the avalanche amplification per one primary electron (Polya function)

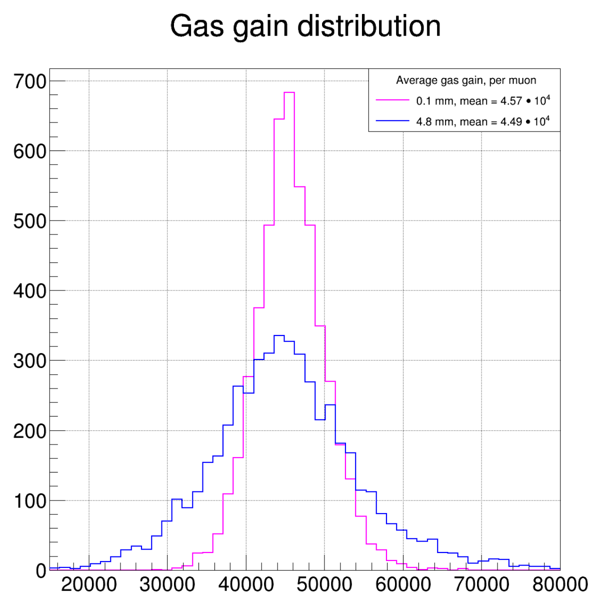


Figure 8. The total charge divided by primary charge for muon track

5. StrawTrackerRD

Figure 9 shows a comparative chart showcasing the results of experiments and simulations. We are pleased to note that the experimental data, obtained in 2023 year with setup at the SPS beam line at CERN, aligns well with our simulation outcomes. This agreement suggests that our temporary solution for adjusting the gas gain is both justified and effective. This result

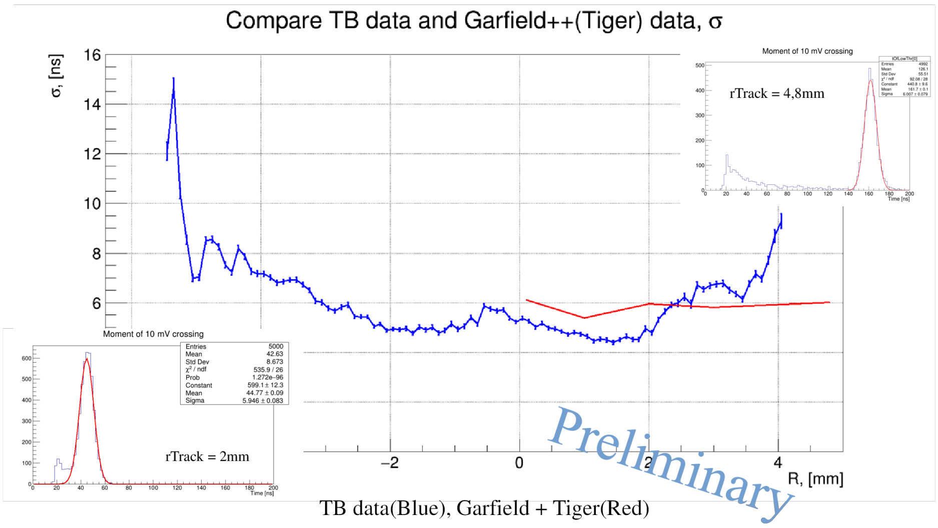


Figure 9. Compare Test Beam data and Garfield++(Tiger) data

underscores the accuracy of our models and approaches. Work in this area is actively ongoing, and we are committed to further refining our methods and technologies.

6. Conclusion

In our research, we have used a combination of Garfield++ and LTSpice to model and predict the performance of straw tube detectors with various readout configurations. This approach allows us to simulate the detector response accurately, providing insight into the behavior of the straw tubes under different conditions. We are currently comparing these simulation predictions with experimental measurements using VMM3 and Tiger ASICs to validate our models. This comparison is crucial for assessing the accuracy of our simulations and refining our techniques.

Additionally, our studies on particle identification (PID) performance are ongoing. These efforts aim to enhance the precision and reliability of straw tube detectors in high-energy physics experiments. By integrating the insights gained from both simulation and experimental data, we are committed to advancing the development of more effective particle detection systems. Our work continues to focus on optimizing readout systems and improving the overall performance of straw tube detectors.

Acknowledgments

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[6] Garfield++ a toolkit for simulating particle detectors based on ionisation in gases and semi-conductors, with features like updated electron transport and silicon sensor simulation: https://garfieldpp.web.cern.ch/garfieldpp/

[7] LTSpice is an electronic circuit simulation software that is widely used for analyzing and designing electronic circuits:
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