Research on Multi-wire Structure Gas Detectors

Authors: Zhang Chunlei, Cao Ligang, Jianwei Huang, Zhang Yaofeng, Yaofeng Zhang

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Abstract

Multi-wire structure gas detectors are widely employed in nuclear physics and nuclear technology fields owing to their advantages of radiation hardness, fast response, large sensitive region, and ease of construction. This paper presents the theoretical methodology for electric field calculation in multi-wire structure gas detectors, and performs electric field optimization design for the drift region and avalanche amplification region utilizing the finite element program ANSYS and the detector simulation program GARFIELD. Additionally, simulation calculations for cosmic rays incident on gas detectors are conducted by integrating the GEANT4 program, yielding statistical results for detector current, voltage, and integrated charge of output waveforms. On this basis, a gas detector is developed and utilized for cosmic ray testing experiments, with experimental results showing good agreement with simulation results. The simulation calculation methods and experimental techniques proposed herein are fully applicable to the optimization design and experimental evaluation of multi-wire structure gas detectors, providing a valuable reference for similar detectors and experiments.

Full Text

Studies on Multi-Wire Gaseous Detectors

ZHANG Chunlei[12], CAO Ligang[12], HUANG Jianwei[3], ZHANG Yaofeng[12]†

[1]College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China
[2]Key Laboratory of Beam Technology and Material Modification of Ministry of Education, Beijing Normal University, Beijing 100875, China
[3]Institute of Ionizing Radiation Metrology, National Institute of Metrology, Beijing 100013, China

Abstract

Multi-wire gaseous detectors offer significant advantages including radiation hardness, fast response, large sensitive area, relatively low cost, and ease of construction, making them widely applicable in nuclear physics and nuclear technology. This paper introduces theoretical methods for electric field calculations in multi-wire gaseous detectors and employs the finite element program ANSYS alongside the detector simulation program GARFIELD to optimize the electric field design for both the drift and avalanche amplification regions. Additionally, GEANT4 simulations were performed for cosmic ray interactions with the gas detector, yielding statistical results for detector current, voltage, and integrated charge from output waveforms. Based on these simulations, a gas detector was fabricated and tested with cosmic rays, demonstrating good agreement between experimental and simulation results. The simulation methodologies and experimental techniques presented herein are fully applicable to the optimization design and experimental evaluation of multi-wire gaseous detectors, providing valuable reference for similar detector systems and experiments.

Keywords: Multi-wire gaseous detector; Electric field calculation; Detector simulation; Cosmic ray measurement

2.1 Theoretical Calculation of Electric Fields in Multi-Wire Electrodes

Multi-wire gaseous detectors typically consist of a drift region and an avalanche amplification region. In the drift region, incident particles undergo ionization, creating initial electron-ion pairs. The ionization electrons drift toward the avalanche amplification region under an external electric field and are subsequently collected. The drift region requires a strong, uniform electric field parallel to the electron drift direction to ensure fast detector response and suppress transverse diffusion effects. The avalanche amplification region utilizes the intense electric field generated near fine wire electrodes (with diameters of several tens of micrometers) to achieve electron avalanche multiplication and signal collection. The avalanche region generally comprises an anode wire plane with equally spaced wires. To ensure electric field uniformity around each wire electrode, ground wire electrode plane arrays with similar periodic structures and grid wire electrode plane arrays with trigger control functionality are often added to the avalanche region. A typical multi-wire gaseous detector structure is shown in [Figure 1: see original paper].

The electric potential produced by wire electrode arrays in their surrounding region can, under ideal conditions (infinitely long in the longitudinal z-direction), be obtained by superimposing contributions from each wire electrode and associated planar electrode unit, enabling derivation of the electric field distribution. For a simple model consisting of a single layer with infinitely many wire electrodes and a single ground electrode plate unit, the potential and electric field distribution can be expressed as [8]:

where the ground electrode plate is located at $y=0$, the wire electrodes are positioned at $x=x_0+k\times s$, $y=y_0$, s represents the wire electrode spacing in the x-direction, k is the wire index, and λ is the charge density on the electrode surface. Equation (1) demonstrates that the electric field around wire electrodes depends not only on electrode geometry but also primarily on the surface charge density λ.

Applying this theory to the multi-wire detector structure shown in [Figure 1: see original paper] and using the applied potentials of each wire electrode group and cathode plate unit as boundary conditions yields:

where λ , λ_9, λ , λ , σ represent the charge densities of various wire electrode units and the cathode plate; r , r_9, r , r are the radii of different wire electrode groups. Solving the equation set (2) yields the charge densities of each unit, and the final detector electric field distribution can be obtained based on equation (1).

2.2 Detector Simulation and Optimization

Actual detectors are constructed with a finite number of wire electrodes, resulting in some deviation from the theoretical calculations of equation (2). Simulation programs are therefore commonly employed for optimization. GARFIELD, developed by CERN, is a comprehensive simulation program for gaseous detectors encompassing electric field calculation, gas medium simulation, electron drift and avalanche processes, and subsequent current response calculations [9]. GARFIELD primarily performs two-dimensional electric field calculations for the detector’ s longitudinal central plane and cannot achieve full coverage of the entire longitudinal region. We utilized the finite element program ANSYS for three-dimensional electric field calculations of multi-wire detectors and imported these results into GARFIELD to enable three-dimensional simulation optimization. The GARFIELD program was modified and recompiled to enable fast and convenient import of electric field data. Meanwhile, new interpolation methods were introduced [10,11] to correct errors in the original program’ s interpolation processing of electric fields near fine wires, obtaining accurate and continuous electric field distributions to ensure smooth subsequent simulation of drift and avalanche processes. For the detector structure shown in [Figure 1: see original paper], the simulated electric field distributions in the central plane for the drift and avalanche amplification regions are presented in [Figure 2: see original paper].

To reduce external interference and improve detector operational efficiency, multi-wire gaseous detectors incorporate grid wires for external trigger control. Grid wire electrodes are divided into odd and even groups based on their arrangement. When necessary, a bias voltage is applied between odd and even groups to generate a transverse electric field in the x-direction in the adjacent region, blocking ionization electrons from entering the avalanche amplification region and placing the detector in an off state. By controlling the grid electrode bias through external trigger signals, the detector' s on/off state can be triggered. Ionization electrons exhibit different transmission efficiencies under different potential conditions, requiring careful selection of grid wire electrode potential and bias values. Theoretical calculations indicate that the electron transmission efficiency is:

where gσ+ and pσ are the charge densities of the grid electrode positive charges and cathode plate, respectively [8]. GARFIELD simulations were performed to calculate detector transmission efficiency under different grid voltage conditions. The comparison between simulation results and theoretical calculations is shown in Figure 3: see original paper, demonstrating good agreement. Figure 3: see original paper presents the calculated ionization electron transmission efficiency under different bias conditions. The results indicate that a grid electrode potential of -110 V with a bias above 35 V is required for effective external trigger control. After extensive simulation optimization, the final detector parameters are listed in .

3. Development and Experiment of Multi-Wire Gaseous Detectors

Based on the detector parameters in , a multi-wire gaseous detector was developed. The detector system is shown in [Figure 4: see original paper]. The detector field cage structure was fabricated using printed circuit boards (PCBs). Copper metal strips with 6 mm width and 4 mm spacing were printed on the PCBs and supplied with equal gradient potentials to establish a uniform drift electric field. Gold-plated tungsten wires were selected for the avalanche region anode wires, while beryllium copper wires were used for ground and grid wires. The wire electrodes were tensioned and soldered onto designed PCB electrode connection boards. A Pad readout board assembly was installed at the detector top and connected to external electronics or oscilloscope sampling through insulated terminals. The detector gas mixture was 90% Ar + 10% CH_4 (P10). The detector body was placed in a vacuum chamber, evacuated to approximately 10^{-3} Pa, and then filled with P10 gas to atmospheric pressure. After applying high voltage to each electrode group, the detector was ready for experiments.

After passing through Earth' s atmospheric shower, cosmic rays near the surface consist primarily of muons with a broad energy spectrum and average energy of approximately 3-4 GeV, capable of penetrating the detector' s vacuum chamber. Cosmic ray muon detection experiments were conducted using the developed multi-wire gaseous detector. During experiments, an oscilloscope was used for direct voltage waveform sampling from the Pad readout board to avoid waveform distortion from electronic readout processing. Simultaneously, Monte Carlo simulations using GEANT4 were performed for the measurement process. Based on cosmic muon energy spectrum data measured by foreign research institutions [12], incident particle energy sampling was performed to simulate ionization positions and electron numbers in the detector. These data were then input into GARFIELD for detector response simulation. The avalanche effect induced by single particle incidence and the corresponding current signals obtained at the anode Pad plane are shown in [Figure 5: see original paper]. The results show that avalanche electrons drift rapidly, producing large-amplitude but short-duration current signals, while ionization ions move slowly, generating small-amplitude but long-duration signals. Due to the Pad structure for signal readout, some ions move toward the Pad readout board while others move oppositely toward the ground wires during experiments. The actual output signal represents the superposition of these two opposite-polarity signals. Based on the simulated current signals and external circuit RC parameters, the simulated pulse voltage waveform for single particle incidence was obtained, showing good agreement with measurement results.

Due to the broad energy spectrum of incident muons, energy deposition fluctuations during ionization in the detector, and fluctuations in gas amplification gain, the detector output voltage pulse amplitude exhibits a large variation range. Consequently, experimental output waveforms were collected and integrated to obtain statistical results of integrated charge for each incident event. Meanwhile, GARFIELD simulations were performed for muon incidence to obtain simulated integrated charge results for muon ionization events. The comparison is presented in [Figure 6: see original paper], demonstrating excellent agreement between experimental and simulation results. This confirms that the detector design optimization methodology proposed in this study is effective, the fabricated detector operates normally, and the measurement results are reliable.

Based on electric field calculation theory for multi-wire gaseous detectors and the GARFIELD simulation program, detector design was performed. Through electric field simulations of multi-wire electrode arrays, appropriate detector structures and potential parameters were obtained. A detector was subsequently fabricated using PCB boards for the drift region, and techniques for soldering, fixing, and tensioning multi-wire electrode arrays in the avalanche region were developed. The fabricated detector was used for cosmic muon measurements, with corresponding simulation studies performed. The statistical results of integrated charge from measured pulse waveforms agree well with simulation calculations. This paper presents development methods and fabrication techniques applicable to multi-wire gaseous detectors and similar TPC detectors.

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