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Simulations of electron avalanches in an ultra-low-background proportional counter

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ABSTRACT

New classes have been added to the simulation package Garfield++ to import the potential and electric field solutions generated by ANSYS ® Maxwell™ v.16. Using these tools we report results on the simulation of electron avalanches and induced signal waveforms in comparison to experimental data of the ultra-low-background gas proportional counters being developed at Pacific Northwest National Laboratory. Furthermore, an improved mesh search algorithm based on Delaunay triangulation was implemented and provided at least a three order of magnitude time savings when compared to the built-in point-location search class of Garfield++.

1. Introduction

There is ongoing research at Pacific Northwest National Laboratory (PNNL) to develop a new capability with ultra-low-background gas proportional counters (ULBPC). The detectors are constructed from ultra-pure electroformed copper that is grown in the 30 m-water-equivalent underground laboratory at PNNL [1]. The electroforming process reduces the majority of uranium and thorium contamination in the copper to produce extremely low-background starting material. These counters are being developed for ground water dating with ^{39}Ar and age dating with ^{14}C and ^{3}H [2].

The applications described above demand an understanding of every pulse registered in the active gas volume to reduce the minimum detectable activity of the system. This includes electron avalanche response from a particle of interest interacting in the gas volume, background induced signals, micro-discharge pulses and other gas breakdown phenomena. In parallel to the experimental effort, simulations can also provide insight to geome trical construction and materials used to increase the fiducial volume while understanding spurious pulses (e.g., gas induced breakdown).

The electric field of a cylindrical, single-wire proportional counter can be solved analytically for much of its length (i.e., $E(r) \approx \frac{1}{r}$) but regions near the ends of the wire can present unforeseen behavior and dielectric material imposed on the geometry increase the difficulty in analytical methods. There are computational methods that can accurately solve (e.g., see Refs. [3,4]) this (non-linear) field configuration with dielectric materials. Another more popular technique for a numerical solution of the electric potential and hence the electric field for a detector model is the finite element method (FEM). The FEM divides an object of interest into smaller elements, in this case tetrahedra, and then calculates the potential and electric field vectors at the nodes which can then be used to interpolate the electric field within each element. Increasing the number of tetrahedra increases the accuracy of the field solution, allowing areas of interest such as the anode wire of a gas proportional counter to be modeled in greater detail than other regions of a model. ANSYS® Maxwell™ v.16 [5] is available at PNNL for a variety of projects to perform electromagnetic modeling. An advantage of using Maxwell is the ability to import the full CAD model of the detector and subsequently solve the potential field. However, implementing FEM to solve the (non-linear) potential of a proportional counter with a linear interpolation can lead to singularities. A common method to "force" an accurate solution near the wire surface is the introduction of "dummy" cylinders into the model, as described in Section 3.1.

Multi-wire proportional chambers, time-projection chambers and single-wire proportional counters are used for measurements in many domains. Garfield [6] was developed to allow interfaces between finite element analysis solutions and a program providing

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Monte-Carlo techniques for electron-ion drift and subsequent signal development of a gas detector. Recently, Garfield has been transitioned to a C++ based program known as Garfield++ (termed here G++) which is used for simulations in this work. G++ has updated transport code (compared to the Fortran version) and a ROOT [7] interface. Magboltz [8] is called by G++ and calculates the parameters of a user defined gas mixture (e.g., the electron drift velocity and Townsend coefficients as a function of electric field) and HEED [9] calculates the ionization created from a particle interaction in the detector medium (primary electron/ion pairs). The Monte-Carlo simulation of electron avalanches is computational intensive and time consuming, especially when the FEM mesh becomes finely spaced and contains many elements (orders of 10^6). This is not an unknown or new problem and other works have implemented techniques to reduce computational time by orders of magnitude. For example, Bonzi et al. found several orders of magnitude (time) improvement by assuming an exponential distribution of electron path lengths between ionizing collisions [10]; eliminating the calculation between successive steps. Also, Alkaa et al. described a technique to reduce computation time by an order of magnitude by eliminating numerical integration of Newtons equations due to the cylindrical symmetry of proportional counters (at pressures above 0.1 atm) [11].

We report the successful results of an effort that produced a simulation path from the computer-aided design (CAD), to accurate finite element method (FEM) solutions of the electric potential of the detector that were then imported into G++. We have reduced the electron avalanche simulation time of G++ by three orders of magnitude by implementing a new point-search algorithm based on a stochastic walk [12] and the Delaunay triangulation. Single-electron and avalanches induced by photon absorption were simulated in a mixture of 3 atm 90% Ar 10% CH_4 (P-10). The gas gain extracted from the simulations is compared to experimental data using a Diethorn plot [13]. Furthermore, simulations provided induced signals in the detector which were then further processed to be directly compared to experimental waveforms acquired by the data acquisition system.

2. The ULBPC apparatus

This section gives a brief description of the ULBPC, more details can be found in Ref. [2]. The detectors are manufactured from ultra-pure electroformed copper which is grown at PNNL [1]. The "crimp end" of the detector is shown in Fig. 1. This end contains a dielectric spring structure (light blue structure in Fig. 1) that centers a small copper cylinder which is crimped around the anode wire inside the cathode wall. The ULBPC gas gain was experimentally measured using $\approx 100\,\mu$Ci of ^{241}Am in sealed source form. The ULBPC was filled with ultra-high purity (99.997%) pre-mixed P-10 (uncertainty of $\pm$ 5% on the CH_4 component) to 2286.38 torr (3.01 atm) [14]. At this pressure, the wire was biased from +2150–2500 V in 50 V increments (counter wall held at ground) for gas gain measurements. Prior to final gas filling, the detector was evacuated to $\sim$0.1 torr and backfilled to 3 atm with P-10 three times. The ^{241}Am allows measurement of the 59.5 keV gamma-ray and also K-shell fluorescence x-rays (8.05 keV [100%], 8.03 keV [$\approx$51%] and 8.9 keV [$\approx$17%]) [15] from the copper cathode wall which then interact in the gas volume. The ^{241}Am sealed source was placed directly against the cathode wall and midway along the wire length to reduce any end effects. A CANBERRA 2006 charge sensitive preamplifier was connected to an SHV-5 bulkhead connector which connects to the wire of the detector through a compression fitting [2]. The preamplifier has adjustable charge sensitivity of either 47 or 235 mV/Mion-pair (47 for this work), diode protected field-effect transistor, pole-zero

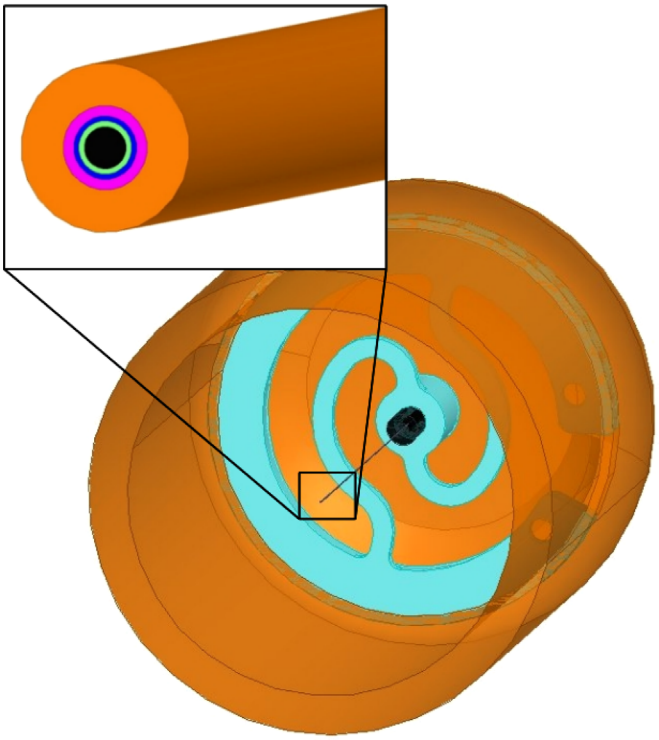

Fig. 1. Cross section of the model used in simulations with a zoom on the dummy cylinders used to control the meshing process. The proportional counter wire was 25 μm in diameter and the cathode had an inner diameter of 2.54 cm. The center black cylinder is the anode wire and the green, blue, magenta, and orange cylinders represent imaginary surfaces of vacuum where Maxwell must form a 2D surface mesh.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adjustment and low noise/fast rise time over a wide range of input capacitance making this a good choice for a proportional counter. Specific details of the preamplifier can be found in the user manual [16]. The output analog waveforms of the preamplifier were digitized with a 75 MHz (1023 samples) Pixie-4 acquisition card [17]. The digital trapezoidal filter had an energy filter flat top of 4.68 μs, rise time of 20.85 μs and a trigger filter flat top and rise time of 0.1064 μs. Waveforms of 13.6 μs with a pre-trigger of 1.5 μs were digitized, analyzed and stored for every event above the trigger threshold. The Pixie-4 ADC channel-to-voltage calibration was accomplished in parallel to taking gas gain spectra and consisted of injecting a fixed charge into the preamplifier and measuring the Pixie-4 ADC channel number. This allowed each photopeak in the energy MCA to be converted from digital channel number to voltage. The experimental energy spectra of each applied voltage was analyzed using ROOT [7] by manually applying Gaussian fits to each peak of interest (8 and 59.5 keV photopeak and test pulse). Subsequently, the number of secondary electrons created in the electron avalanche was calculated using the charge sensitivity of the preamplifier from which the gas gain was derived.

3. Prototyping method and simulations

3.1. Finite element modeling in Maxwell

To simulate the gas gain of the ULBPC, a geometrical model of the physical device was created in SolidWorks®. The SolidWorks model was exported in ACIS-SAT format then imported into Maxwell where materials and boundary conditions are assigned.