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Three-dimensional electric field calculations for wire chamber using element refinement method in ANSYS

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Abstract Finite element analysis (FEA) method was employed to perform three-dimensional (3D) electric field simulations for gas detectors with multiple wire electrodes. A new element refinement method developed for use in conjunction with the FEA program ANSYS allows successful meshing of the wires without physically inputting the wires in the chamber geometry. First, we demonstrate a model with only one wire, for which we calculate the potential distributions on the central plane and the end-cap region. The results are compared to the calculations obtained using GARFIELD, a two-dimensional program that uses the nearly exact boundary element method. Then we extend the method to same model, but with seven wires. Our results suggest that the new method can be applied easily to the 3D electric field calculations for complicated gas detectors with many wires and complicated geometry such as multiwire proportional chambers and time projection chambers.

Keywords Finite element analysis · Time projection chambers · Nearly exact boundary element method

1 Introduction

In modern nuclear physics, most gas detectors have multiwire configurations [1–4]. These wires are biased to high voltage to create an avalanche region, which amplifies the production of drift electrons by a charged particle traversing through the detector [5]. Nonuniformities in the electric field can affect the detector performance and reconstruction of particle tracks within the detector. While designing such detectors, it is necessary to simulate the electric field for ensuring uniform electric field. Data analysis requires the knowledge of nonuniform electric field regions. There are a variety of methods to perform electric field simulations. Each method comes with characteristic strengths and limitations. In symmetric situations, a two-dimensional approach, such as GARFIELD [6], using a nearly exact boundary element method (NEBEM), is sufficient. Investigating more complicated geometry may require three-dimensional (3D) simulations [7, 8]. In this study, we focus on a new method incorporated into the finite element analysis (FEA) to perform 3D electric field simulations. 3D simulations that use the typical FEA often fail or produce incorrect results even for relatively simple configurations such as a box containing a long, thin wire. The high length-to-diameter (LD) ratio of the wire requires breaking the problem into a large number of small, finite elements to produce accurate results. However, the

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extremely large number of elements increases the complexity of calculation making it impossible to perform the calculation with standard programs. We investigate the 3D simulation of a wire with an LD ratio of more than 10^5 using a new approach to address such challenges. We demonstrate that this method can reproduce the results for configurations that can be calculated in two dimensions. We also show that this method can be easily expanded to the 3D electric field calculation for complicated detectors with many wires.

2 Principles of FEA calculations with element refinement method

FEA is a method for solving physical problems where finding an analytical solution may not be practical. FEA solves the problem by meshing, which means constructing an array of finite elements with a regular geometry. These finite elements can be defined by nodes at the vertices and at the mid-points of the lines that connect the vertices. Application of boundary conditions and initial values to these nodes provides a system of equations that can be solved to provide a numerical solution for the real problem [9]. The typical method for FEA calculations can be broken into steps: First, build the model by including all the information pertaining to geometry. Second, mesh the model into a system of finite elements. Third, apply the boundary conditions to all the related nodes, and finally, solve the system of equations thus obtained.

For a wire in a box, the typical meshing procedure uses either a sweeping method or a free meshing method, as illustrated in Fig. 1. The sweeping method (left panel) attempts to match the geometry of the system, while the free meshing method (right panel) produces a high density mesh thus providing sufficient nodes to reproduce the system. The meshing can fail in case of the sweeping method when the LD ratio of elements in the calculation is too high. The free meshing method may fail if the meshing results in too many elements in calculation. Even if free meshing is successful, the large number of elements can still lead to a failure in the subsequent solving procedure. Thus, wire electrodes with an LD ratio of more than 10^5, as in typical nuclear detectors, pose a significant challenge to the meshing process. In this study, we describe a new method which we refer to as the element refinement method to overcome the above problems.

As shown in Fig. 2 for the elements refinement method, first, the bulk volume is built without including any wire geometry. Second, the model is meshed, using the sweeping method. Third, the element refinement method is used to refine the elements in the wire-located region so that enough elements can be generated to approximate the geometry of the wire accurately. This method produces node densities suitable for accurate representation of the boundary conditions for the wire, while maintaining suitable number of total elements for FEA calculations. The fourth and fifth steps involve the usual method of applying boundary conditions and solving the system of equations. Script codes can be used to perform all the steps automatically to calculate the electric field.

With the element refinement method, only the bulk volume must be built, excluding the wires. The method bypasses the meshing problem by selectively refining node density where it is needed. The reduced number of elements and the lack of finite elements with a high LD ratio bypass the problems encountered in the typical methods. In the case of a one-wire model, typical sweeping method allows an LD ratio of up to 3×10^4. Additional wires will increase the required number of finite elements and will consequently decrease the maximum LD ratio. In contrast, for the element refinement method, we have successfully

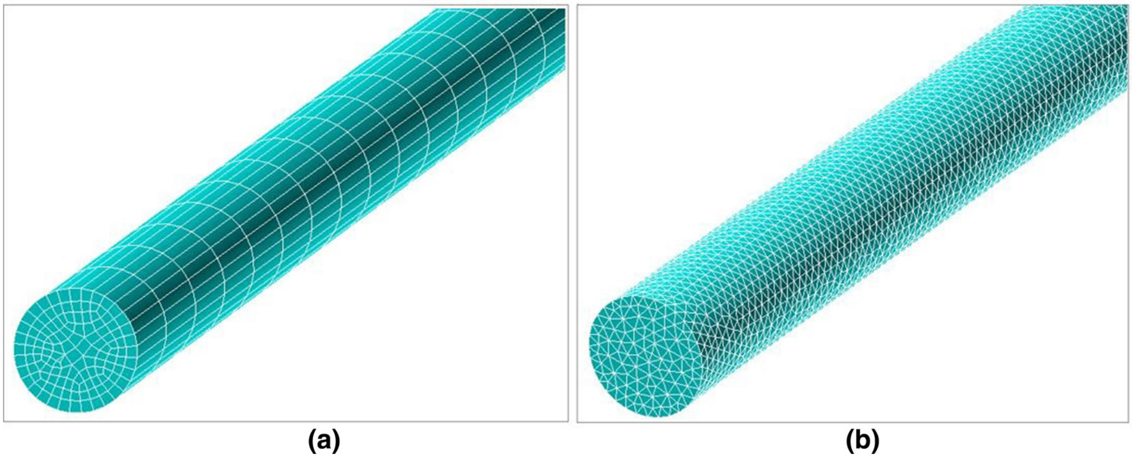

Fig. 1 (Color online) Two ways of meshing method for a wire **a** sweeping method, **b** free meshing method

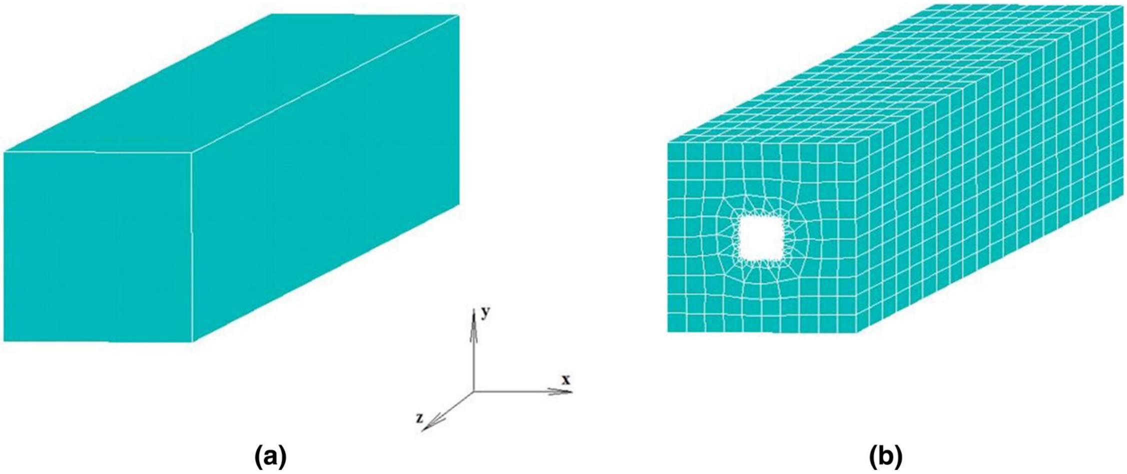

Fig. 2 (Color online) Key steps of the new method to accomplish 3D field calculation for wires. **a** Build a bulk body without any wire **b** use meshing and refinement for the related elements to describe the wire

tested the one-wire model or multiwire model for LD ratio of 5×10^5. In principle, this method is independent of the LD ratio and number of wires in the system.

3 3D electric field calculation for single wire chamber

The simulations in this study were performed with ANSYS, a popular commercial FEA software, which has been used successfully in various fields such as simulation of static electric fields, static magnetic fields, radio frequency problems, and in mechanics and engineering thermodynamics. It was chosen for its features of powerful functions in nodes operation [10], which facilitates the performance of the necessary element refinement.

To illustrate the problems with high LD ratio and to demonstrate our method, we perform FEA ANSYS simulations on a simple model, illustrated in Fig. 3, consisting of a rectangular volume with a single wire running through the middle. The wire is 60 cm in length and 2 μm in diameter for an LD ratio of 3×10^5 and it is biased to a voltage V. The rectangular volume is 100 cm long with a cross section of 20 cm × 20 cm. All the external faces are held at ground potential.

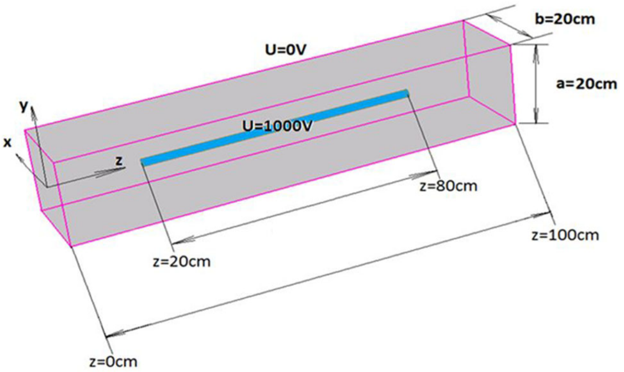

Fig. 3 (Color online) The schematic diagram for the simple checking model with only one wire

3.1 Key steps to do 3D electric field calculation for the model

The meshing process is a key step to do calculations for FEA ANSYS. A successfully meshed model with an appropriate number of elements ensures an accurate 3D electric field calculation. For the one-wire model illustrated in Fig. 3, we adopted different meshing methods for different regions of the model. In the middle region, which contains the wire (from $z = 20$ cm to $z = 80$ cm), we meshed it using the sweeping method, followed by elements refining method. For the other two end-cap volume regions ($z = 0$ cm to $z = 20$ cm and $z = 80$ cm to $z = 100$ cm), the free meshing method was used. The meshed models are shown in Fig. 4.

Boundary conditions were applied after the meshing process. The wire in the model had a potential of 1000 V. To model the wire, all the nodes at the wire-located position were selected and the boundary value was set to the electric potential. The sweeping method used in the meshing process allowed us to create an accurate region for the wire. The meshed model is shown in Fig. 5, with the boundary condition application shown in green. The boundary condition can be efficiently applied for the wire through ANSYS parametric design language script codes.

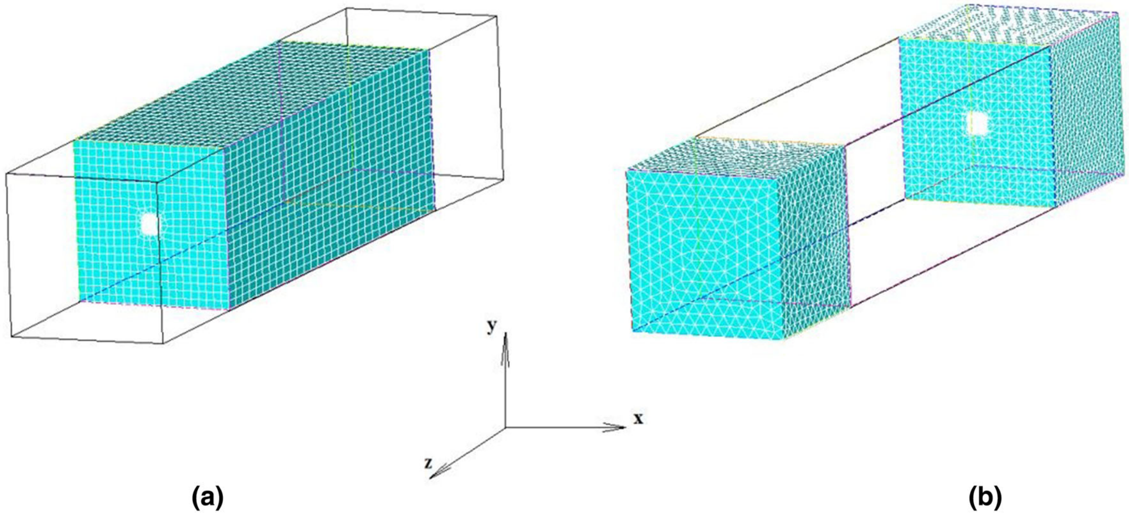

Fig. 4 (Color online) Meshed model for a one-wire chamber: **a** for middle part, using sweeping method. **b** For two edge regions, using free meshing method

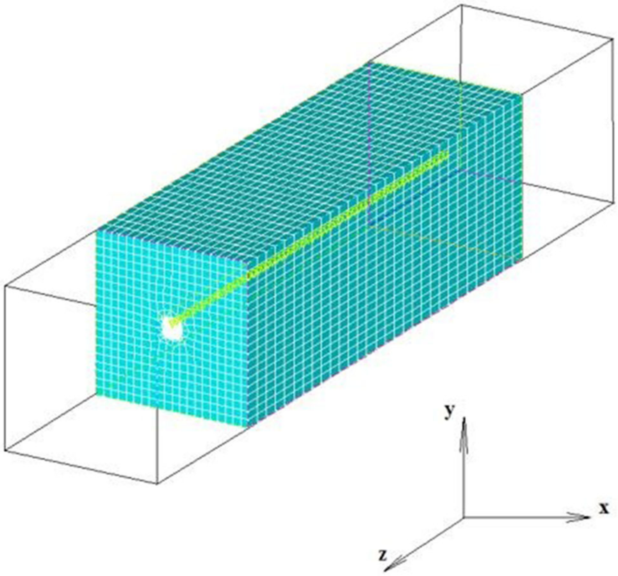

Fig. 5 (Color online) The model after application of the boundary condition of the wire

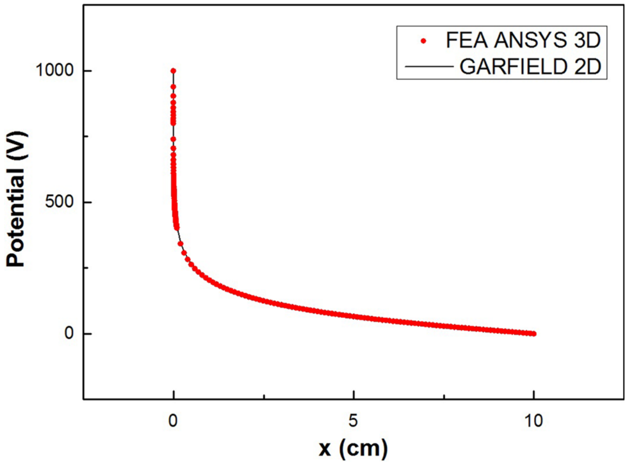

Fig. 6 (Color online) The equipotential distribution along the *X*-axis on the central plane (z = 50 cm)

3.2 Electric field distribution on the central plane for the model

In principle, we can determine the electric field at any point for the model. We first calculated the electric field in the central plane ($z = 50$ cm), as the field in this region was also calculated by the two-dimensional (2D) GARFIELD program. This allowed us to compare the results obtained using 3D FEA ANSYS and 2D GARFIELD and verify the FEA method. Figure 6 illustrates the potential distribution along the *X*-axis at the central plane (z = 50 cm). The results from both the calculations were found to be in good agreement, reaching a maximum difference of 1% of the potential at the edges of the central plane, where the potential drops to 0. The deviation is related to the degree of accuracy of the generated nodes to represent themselves as the true surface of the wire. Although significant number of nodes are critical to get accurate electric field results, this may lead to a more complicated meshed model. A balance between precision of the results and the complexity of the meshing is needed to obtain a successful solution of the electric field calculation. The agreement demonstrates that FEA method can be applied to the 3D electric field calculation of the one-wire configuration model.

3.3 Electric field distribution in the edge region for the model

In this section, we analyze the end-cap region of the model which cannot be obtained with a 2D GARFIELD simulation. Figure 7 shows the distributions of the electric potential on an *xy*-plane located at z = 90 cm, which is in the middle of the rightmost end-cap region. The potential V_0 at the center of this square is about 6.3 V, and the equipotential distribution near the center has circular shapes. The shapes change from circle to square as one moves from the center to the edge. For other z positions, similar distributions are obtained and the potential V_0 depends on the z position. As shown in Fig. 8, the potential V_0 for the central positions has a similar distribution along Z-axis as the one shown in Fig. 6, but here V_0 decreases more steeply.

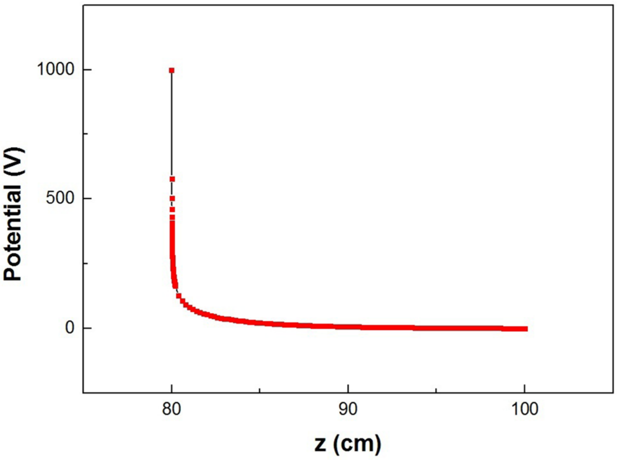

Fig. 8 (Color online) The distribution of potential V_0 along Z-axis for the edge region of the model

4 Application to 3D electric field calculation for a multiwire model

Since the geometry of the wires does not have to be described explicitly in the new method, it can be easily expanded to 3D electric field calculation for detectors with many wires. It decreases the complexity of the model significantly and ensures the calculation with high efficiency. As an example, we use the new model with seven wires equally distributed along X-axis from $x = -1.2$ cm to x = 1.2 cm with a pitch of 0.4 cm. The model is very similar to that in Fig. 3. The only difference from the one-wire model is the larger wire-located region which must be selected for element refinement. All the wires have a diameter of 20 μm and length of 60 cm, corresponding to LD ratio of 3×10^4. Similar to the model in Fig. 3, the two end-cap regions span from z = 0 cm to z = 20 cm and z = 80 cm to z = 100 cm. The meshed model is shown in Fig. 9. The elements refined region appears in a rectangular shape and covers an area that contains all the seven wires in the *xy*-plane.

Figure 10 shows the equipotential distribution for the near wire region on the central plane. Each wire has its own

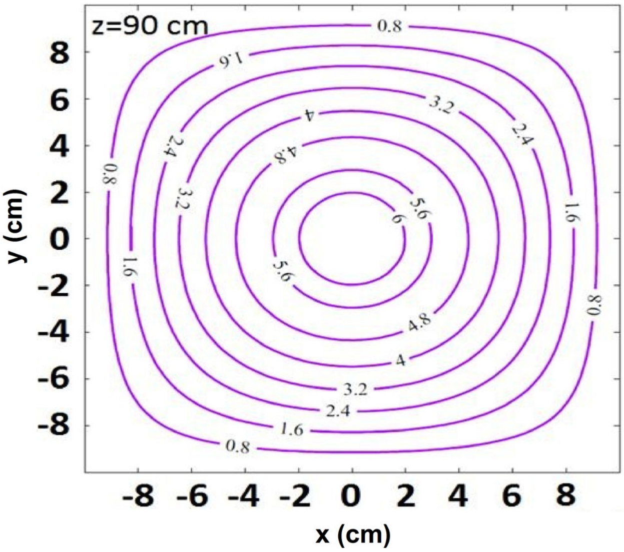

Fig. 7 (Color online) The equipotential distribution for the model on a z = 90 cm *xy*-plane

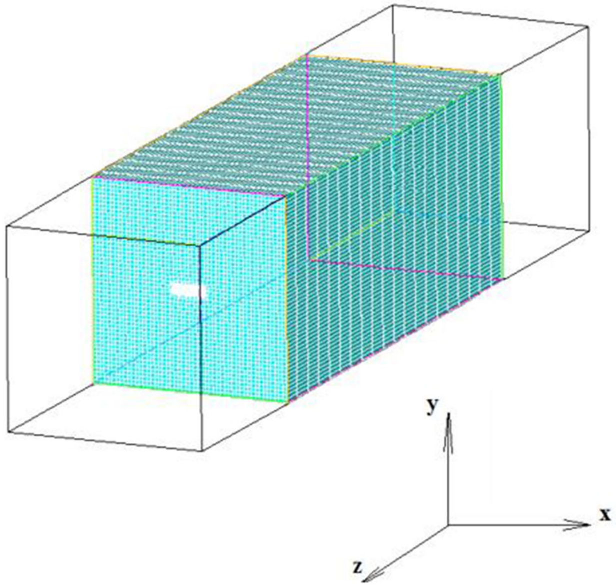

Fig. 9 (Color online) The meshed model in the region containing seven wires

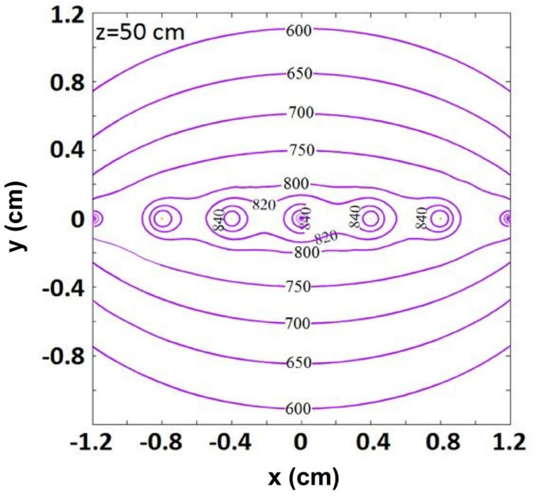

Fig. 10 (Color online) The equal potential distribution on central plane for the seven-wire model

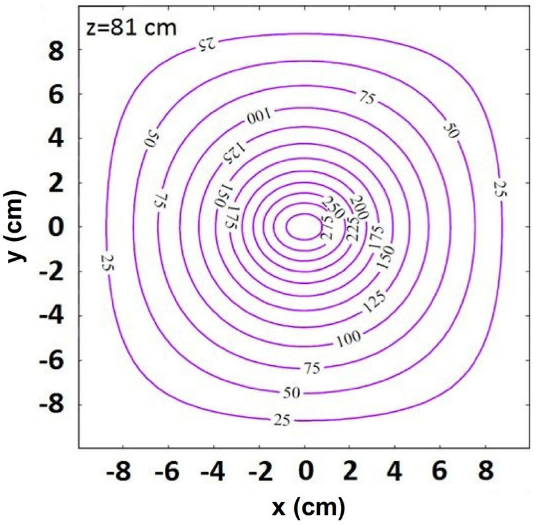

Fig. 11 (Color online) The equal potential distribution in the edge region for seven-wire model

distribution of near circular shape in the area very close to its surface, while the distribution in the surrounding area shows elliptic shaped lines. With an increasing number of wires, the equipotential lines become straight lines, indicating a more uniform electric field. The electric field distribution in the end-cap region of the model is shown in Fig. 11. At the center of the plane, the equipotential lines take on an elliptic shape, which shows the effect of the wire distribution on the field in the end-cap region.

5 Summary

The element refinement method is employed to explore a new way to perform 3D electric field calculations using FEA ANSYS for wire configurations with high LD ratios. The calculated results using FEA ANSYS and 2D GARFIELD on the central plane of the model agree well. The comparison demonstrates the validity of the current method. The new method allows successful meshing process without the input of geometry of individual wires. Thus, this method can be easily expanded to perform 3D electric field calculations for complicated detectors with multiwire geometry such as MWPC and TPC, frequently used in nuclear experiments.

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