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A study of electric field distribution in Benjamin type proportional counter using finite element method

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HIGHLIGHTS

- Radical and axial electric field distribution in Benjamin-type proportional counter were calculated using 3D finite element method.
- The calculated results can be verified with experimental results.
- The axial electric field distribution was observed that shows the characteristics of a cylindrical counter.
- Alternative optimizations were analyzed and discussed for TEPC uses.

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ABSTRACT

Tissue equivalent proportional counters (TEPCs) are commonly based on the Benjamin type of concept. Initially the electric field is optimized by pulse height measurement methods and only one optimum solution was established at that time. In this paper, the electric field distribution is analyzed and optimized using a three-dimensional finite element method. The calculations show that the characteristics of the radial electric field distribution of this type of counters can be equated to cylindrical counters using a pair of appropriate field shaping electrode. Furthermore, the paper analyzes the axial electric field distribution and the possibility of achieving a uniform electric field along its anode while reducing the size of Benjamin type proportional counter design down to 1/10 of currently feasible values with respect to the thinnest available anode wire diameters.

1. Introduction

The advantage of proportional counters of spherical shape is their symmetrical response with respect to isotropic or directional radiation. When designing a spherical counter, it is critical to ensure a uniform electric field along its anode wire similar to that of a cylindrical counter. Deviation from this cylindrical field geometry causes inhomogeneous gas multiplication in the counter which leads to a loss of energy resolution. The Benjamin type proportional counter was introduced in the 1960s and first utilized as spherical hydrogen filled proportional counter for low energy neutron spectrometry (Benjamin et al., 1968). Later on it was widely commissioned as a design for tissue equivalent proportional counters. Experimental studies by Waker show that the volume-averaged fractional distortion of the electric field uniformity along the counting wire in low pressure Benjamin type proportional counters is about 1% and close to the value reported by Benjamin. Besides, the resolution of a Benjamin type TEPC agrees well with a Rossi counter (Waker, 1985, 1986). The Rossi counter, which is an alternative and the original design of a spherical TEPC ensure a uniform electric field distribution by adding a helical electrode concentric to the anode wire (Rossi and Rosenzweig, 1955a, 1955b). The disadvantage of this helical electrode is its sensitivity to vibrations, which is an undesired property in non-stationary applications such as aviation and space missions (Perez-Nunez and Braby, 2011; Braby, 2015). Moreover, recently a hemispherical proportional counter was proposed and the avalanche characteristics of this counter was calculated analytically. It was concluded in the paper that this technique is a promising candidate for experimental dosimetry (Broughton and Waker, 2016).

In the Benjamin type proportional counter a uniform electrical field is approximated by using a pair of conductive wire supports of a larger diameter than the anode wire, but on the same potential, to balance the

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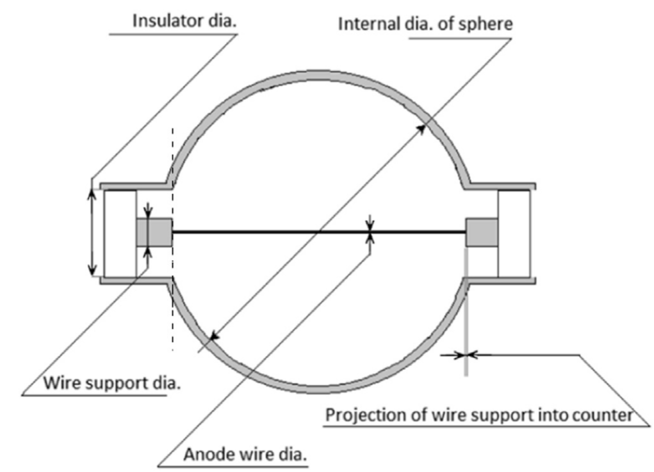

Fig. 1. Layout of Benjamin type proportional counter.

electric field towards the smaller cathode diameters near the ends of the wire, as is illustrated in Fig. 1. It was not possible at that time to calculate the electrical field inside the sphere numerically or by analytical methods. Benjamin et al. optimized the electrical field distribution experimentally, by constructing a large test counter and adjusting the dimension of each part by measuring the gas amplification at several defined axial positions along the wire (Benjamin et al., 1968). From these measurements and variation of the geometry of the counter he derived the following set of optimal parameters:

- *Internal diameter of sphere = D,*
- *Insulator diameter = 0.257D,*
- *Wire support diameter = 0.114D,*
- *Anode wire diameter =* 5.5×10^{-4}*D,*
- *Projection of wire support into counter = 0,*
  (all the parameters are explained in Fig. 1)

This set of dimensions defines the template for all models of Benjamin type counters. It is currently understood that the critical dimensions for the constancy of electrical field are the diameter of the insulator, the diameter of the anode wire, the diameter of the wire support and the projection of the anode wire support (Tagziria and Hansen, 2003). However, the correlation between these dimensions and the electrical field distribution is ambiguous. Different from their use in neutron spectrometry, in some microdosimetric applications a TEPC should be rather small to simulate tissue volume of small size. In practice the size of the counter is limited by the available thin anode wire when using Benjamin's optimal set of parameters. For decades no further studies of how Benjamin type proportional counter can be modified or if the concept can be further optimized were published. Recently, some reports in developments of Benjamin type spherical TEPC appeared (Jiang et al., 2015; Straume et al., 2015; Collums et al., 2014). In Jiang's construction the TEPC strictly conform to the Benjamin's template (Jiang et al., 2015). We also note that in the report of Straume the diameter of anode wire is about 2 times larger (Straume et al., 2015). In this work we aim to investigate the correlation between the electric field and the dimensions of each part of the counter for further optimizing the TEPC development. In particular we aim for the possibility to obtain a uniform electric field with a larger ratio of anode diameter to the diameter of the internal sphere.

Nowadays, the finite element technique provides a numerical approach for the calculation of the electrical field in nearly arbitrary electrode geometries. Using these tools the field distribution in the Benjamin type design is calculated along the anode wire as well as in radial direction. The correlation between the dimension of if each part of the counter and the electric field distribution were analyzed and

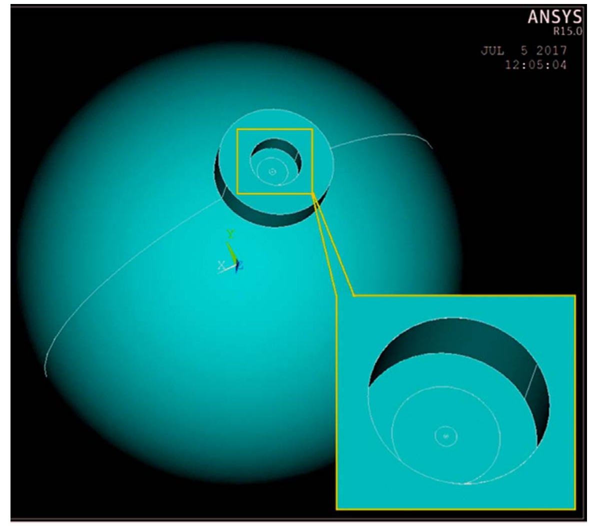

Fig. 2. Model built in ANSYS.The counter is subdivided into several sub volumes around the wire axis before meshing.

possible alternative solutions are discussed. A comprehensive understanding of the electric field distribution in this type of proportional counter, which can facilitate the electron avalanche modeling for a TEPC counter, is essential for interpreting the measurements performed by a TEPC (Ségur et al., 1995).

2. Simulation methods

The ANSYS15.0 software is used to model and calculate the electric field inside the detector. The analysis of the electric field in a spherical model is more complicated than in cylindrical counter and a three-dimensional model must be applied for the calculation. Since there is a huge difference between the size of the spherical cathode and the anode, the model is carefully divided into several sub volumes before meshing to improve the quality of results, as is illustrated in Fig. 2. The surface of the wire support and the anode wire are biased with a positive high voltage while the internal surface of the cathode sphere is defined to ground potential. The electric field distribution in the gas filled volume of the counter was modeled based on the potential on the electrodes. The working gas was chosen to be Argon at 1 bar pressure. For this, the relative permittivity is set to 1. As there is only one substance in this model, the characteristics of electric field distribution in the counter are independent of the filling gas properties. However, the gas amplification depends on the electric field distribution, as well as on gas composition and gas pressure in the counter. Gas gain in atmospheric pressure can be calculated by Townsend theory (Nasser, 1971).

$$\frac{\mathrm{dn}}{\mathrm{n}} = \frac{\mathrm{dx}}{\alpha} \tag{1}$$

where n is number of electrons produced per path length dx. αis the first Townsend coefficient. The empirical formula suggested by Townsend is:

$$\alpha = \mathrm{A\ p}\exp\left(-\frac{\mathrm{Bp}}{\mathrm{E(x)}}\right) \tag{2}$$

where p is the gas pressure. A and B are constants characteristics for a specific gas composition.

In a proportional counter gas multiplication happens only in a small region near the anode wire, therefore integration of Eq. (2) between ∞ and the anode radius R_a provides the number of electrons M, which is equivalent to the gas gain:

$$\mathrm{M} = \exp\left(\frac{\mathrm{AE_aR_a}}{\mathrm{B}}\exp\left(\frac{-\mathrm{pB}}{\mathrm{E_a}}\right)\right) \tag{3}$$