Nuclear Instruments and Methods in Physics Research A 840 (2016) 107–112

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

An analytical comparison of gas gain in spherical, cylindrical and hemispherical low-pressure proportional counters intended for use in experimental microdosimetry

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ARTICLE INFO

Keywords:
Gas gain
Proportional counter
Townsend equation
Microdosimetry
TEPC

ABSTRACT

Traditionally experimental microdosimetry has employed low pressure single cavity spherical Tissue Equivalent Proportional Counters (TEPCs). Multi-Element Tissue Equivalent Proportional Counters (METEPCs) with numerous cylindrical cavities have been constructed in order to increase sensitivity per unit volume; however existing METEPC designs are prohibitively complex and sensitive to motion and audible noise. This work proposes a novel hemispherical element with a wire-less anode ball as a solution to these issues. The gas gain characteristics of this hemispherical METEPC element were analyzed first for a single hemispherical TEPC to evaluate performance relative to current cylindrical and spherical counter designs that have been demonstrated experimentally to perform very well. This gain analysis evaluated relative avalanche size and the uniformity in maximum gain for electrons originating throughout the gas cavities of each of the three counters. Radial gas gain distributions for each counter were determined using both theoretical potential distributions as well as analytical equipotential distributions generated with ANSYS Maxwell (V. 14.0) to solve the Townsend equation. It was found that the hemispherical counter exhibits completely uniform gas gain for electrons approaching the anode from all directions and its avalanche region occupies only 3.5×10^{-3}% of the entire gas cavity volume, whereas in the cylindrical and spherical counters the avalanche occupies 0.6% and 0.12% of the total respective gas cavity volumes. These analytical gas gain results are promising, suggesting that the hemisphere should exhibit uniform signal amplification throughout the gas cavity and if the recommended follow-up experimental work demonstrates the hemispherical counter works as anticipated it will be ready to be incorporated into an METEPC design.

1. Introduction

Experimental microdosimetry is one of the very few means of performing real-time measurements of both absorbed dose and ionization density based quality factors and thereby dose equivalent. Traditionally this has been achieved by using tissue equivalent proportional counters (TEPCs) of spherical geometry, consisting of a tissue equivalent (TE) cathode shell, a central anode wire and filled with low pressure TE gas, allowing a microscopic tissue site to be simulated using a macroscopic detector. As TEPCs with a single gas cavity have relatively low neutron sensitivity [counts/Sv], multi-element TEPCs (METEPCs) have been proposed for the low intensity neutron fields most often encountered in radiation protection. The first METEPC was constructed by Rossi in the 1980s and consisted of 296 cylindrical elements 0.3175 cm by 0.3175 cm (1/8 in by 1/8 in) [1]. All experimentally tested METEPCs to this date have also employed cylindrical elements, largely due to the fact that they are much easier to machine and tightly pack relative to spherical elements.

The concept of the METEPC has been demonstrated to work very well for the purpose of increasing counter sensitivity per unit volume. However, the complexity of existing designs has made them cost prohibitive beyond research applications. The challenges in METEPC manufacturing are largely due to the use of an anode wire, which requires very precise installation and must be some tens of microns in diameter to yield both suitable energy resolution and high gas gain. Additionally, in both spherical and cylindrical counters the anode produces end effects where the decreased distance from anode to cathode near the ends of the wire increases the magnitude of the local

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Abbreviations: TEPC, Tissue Equivalent Proportional Counter; TE, Tissue Equivalent; METEPC, Multi-Element Tissue Equivalent Proportional Counter; THGEM, THick Gas Electron Multiplier

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http://dx.doi.org/10.1016/j.nima.2016.09.048
Received 23 June 2016; Received in revised form 12 September 2016; Accepted 21 September 2016

electric field. Reducing these end effects requires the use of additional electrodes such as septa [1], or anode extensions [2] which do produce a substantially uniform electric field, while also further complicating the manufacturing process.

As an alternative to wired proportional counters the most recently reported simulated METEPC design employed THick Gas Electron Multipliers (THGEMs) [3], however Monte Carlo simulations found that the standard THGEM design exhibits significant directional dependence in 1 MeV fast neutron fields, requiring additional TE modifiers that increase the complexity of the proposed THGEM-based METEPC design [4]. As reports are yet to be made regarding the manufacturing of such counters it is unknown whether the design is prohibitively complex for ready commercialization.

The proposal presented in this work is to use hemispherical counters where the usual anode wire is replaced by a ball anode as the repeated element in a multi-element device. Although a hemispherical counter may have as low as half the sensitivity of a spherical counter of the same radius [5] any number of elements can be used to obtain the required sensitivity in an METEPC. The manufacture of an array of hemispheres and the use of a ball anode should in principle be easier than that for a similar array of spheres. This work reports on an analysis of the gas-gain characteristics of the proposed counter element; dosimetric considerations such as the influence of chord-length distributions of interacting charged particles with hemispherical as opposed to spherical geometry have been addressed in a sister publication [6].

2. Proportional counters for analysis

2.1. Proposed hemispherical design

As a result of the considerations outlined above an alternative to both the THGEM-based and wired cylindrical METEPC element designs is being pursued. Since existing wired counters do exhibit very good gas gain characteristics they can be used to benchmark those of the proposed design. The main objective for the new design is to simplify manufacturing without compromising gas gain performance. The proposed design described in this work stemmed from a qualitative 2D electrostatic investigation using detectors of various geometries performed with the software ANSYS Maxwell version 14.0. ANSYS Maxwell employs an iterative electrostatic solver to numerically solve the 2D Maxwell equation, producing electric field and equipotential distributions defined at finite nodes throughout the user input geometry. This preliminary investigation was reported in [5] and found concentric symmetry between the surfaces of the anode and cathode to be the main predictor of uniform electric field distributions in the region adjacent the anode, which would correspond to a uniform gas gain. This led to a counter design consisting of a hemispherical cathode and a concentric anode ball, as illustrated in Fig. 1..

For a spherical anode the electric field at a given potential difference between anode and cathode is proportional to the inverse of the square of the anode radius. Hence the highest gas gains can be achieved with the smallest anode diameters. In developing the hemispherical design, the cathode and insulator diameters were optimized for a 0.04 cm diameter anode ball as 0.04 cm was found to be the smallest commercially available electrically conductive ball brazed onto a metal stem (Bal-tec™, L.A., California). A series of electrostatic analyses were conducted and reported in [5] using the 0.04 cm anode ball with various insulator and cathode diameters. These analyses were aimed at determining the dimensions capable of producing a reduced electric field, $(E/p)_a$ [V cm^{-1} Torr^{-1}], within the same range as the experimentally demonstrated spherical and cylindrical counters, while also maintaining a nearly isotropic electric field distribution around the anode [5]. The hemispherical dimensions capable of doing this were 2.54 cm diameter for the hemispherical cathode shell and 0.44 cm diameter for the insulator. This proposed hemispherical design could have several benefits over wired counters and THGEM designs. Reducing the number of components should simplify the manufacturing process, and having the anode ball fixed in place may reduce or eliminate sensitivity to microphonic noise, which is an issue with wired counters.

2.2. Existing reference detector designs

In order to properly evaluate gas gain characteristics two counters which have been demonstrated experimentally to perform very well in terms of gas gain were also included in the analysis. The first counter is based on a standard commercial detector for radiation protection microdosimetry, the 12.7 cm diameter single-wire spherical TEPC manufactured by Far West Technology Inc. (Goleta, California). The second counter design is a single cylindrical element 0.5 cm diameter 5 cm height as used in the 61 element cylindrical METEPC design of Waker [2]. The relevant parameters of these two detectors are presented along with those of the hemispherical counter in Table 1.

3. Method of gas gain analysis

3.1. General gas gain theory

The process of electron multiplication as electrons drift towards the anode of a proportional counter is referred to as gas gain. Analysis of gas gain may be conducted either using the stochastic Monte Carlo method which involves tracking individual electrons and the outcomes of each interaction, or using the deterministic semi-empirical method which uses the mean probability of ionization per unit path length to determine the mean gas gain. For this study the semi-empirical method is applied as it has been recommended by others to be an appropriate means for characterizing gas gain parameters in TEPCs [7]. The specific parameters under investigation here include the relative volumes of the electron avalanches (where 97% of gas gain occurs) and the uniformity of gain for electrons originating at points throughout the gas cavity.

The calculation of the total gas gain is based on the integration of the Townsend first ionization coefficient, $\alpha(r)$ [ion pairs cm^{-1}], from the radius of the anode to the cathode, referred to as a and b, respectively

$$\ln(G) = \int_a^b \alpha(r)\,dr \tag{1}$$

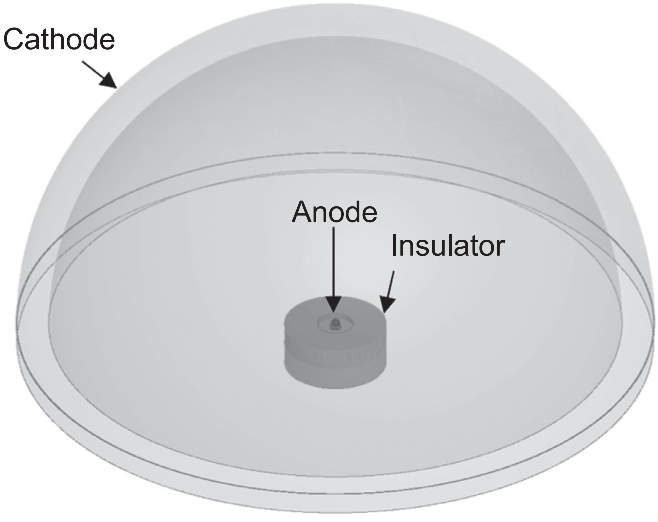

Fig. 1. Isometric view from above of proposed TEPC design consisting of 2.54 cm diameter hemispherical cathode with a concentric 0.04 cm diameter spherical anode and a 0.44 cm diameter insulator