FIRE: A compact nanodosimeter detector based on ion amplification in gas

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Abstract: One goal of nanodosimetry is to determine statistical quantities of ionization distributions in nanometric volumes. It is hypothesized here that these quantities are related to the initial biological damages in DNA from ionizations. Thus nanodosimetric quantities will potentially complement or replace the concept of RBE-weighted absorbed dose and hence they could be applied in treatment planning systems, risk assessments for radiation protection and space radiation. The development of a compact and portable nanodosimeter detector available for clinical routine is a significant step towards that goal. We present extensive measurements to characterize the performance of the FIRE (Frequency of Ion REGistration) nanodosimeter detector. It operates on similar principles like the Gas Electron Multiplier (GEM). Contrary to GEMs the FIRE detector registers positive ions instead of electrons and operates at low pressures of 0.5 Torr to 2.5 Torr. In addition, the FIRE nanodosimeter capitalizes on the usage of a resistive cathode in order to suppress discharges. Moreover, the geometry of the FIRE detector is adapted to the low pressure by enlarging the typical dimensions of a GEM foil by two orders of magnitude. The authors present two configurations of the compact FIRE nanodosimetry detector. The resistivities of the two configurations differ by six orders of magnitude. The lower resistivity should allow for faster removal of the charges attached to the wall inside the hole channel. Measurements of mean number of ions produced by 5MeV alpha particles in low pressure propane gas, mean number of dark counts, the ion arrival time, and the mean avalanche charge are presented. The dependency of these parameters on acceleration voltage, drift voltage, pressure and hole diameter were investigated.

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FIRE: A compact nanodosimeter detector based on ion amplification in gas

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ABSTRACT

One goal of nanodosimetry is to determine statistical quantities of ionization distributions in nanometric volumes. It is hypothesized here that these quantities are related to the initial biological damages in DNA from ionizations. Thus nanodosimetric quantities will potentially complement or replace the concept of RBE-weighted absorbed dose and hence they could be applied in treatment planning systems, risk assessments for radiation protection and space radiation. The development of a compact and portable nanodosimeter detector available for clinical routine is a significant step towards that goal. We present extensive measurements to characterize the performance of the FIRE (Frequency of Ion REgistration) nanodosimeter detector. It operates on similar principles like the Gas Electron Multiplier (GEM). Contrary to GEMs the FIRE detector registers positive ions instead of electrons and operates at low pressures of 0.5 Torr to 2.5 Torr. In addition, the FIRE nanodosimeter capitalizes on the usage of a resistive cathode in order to suppress discharges. Moreover, the geometry of the FIRE detector is adapted to the low pressure by enlarging the typical dimensions of a GEM foil by two orders of magnitude.

The authors present two configurations of the compact FIRE nanodosimetry detector. The resistivities of the two configurations differ by six orders of magnitude. The lower resistivity should allow for faster removal of the charges attached to the wall inside the hole channel. Measurements of mean number of ions produced by 5MeV alpha particles in low pressure propane gas, mean number of dark counts, the ion arrival time, and the mean avalanche charge are presented. The dependency of these parameters on acceleration voltage, drift voltage, pressure and hole diameter were investigated.

1. Introduction

It is well known that the biological effectiveness of radiation depends on particle type and energy and not only on the amount of deposited energy per mass (i.e. absorbed dose). It is nowadays a well accepted consensus in the scientific community that inelastic interactions in and around the DNA (deoxyribose nucleic acid) molecule are of high importance in the origin of radiation-induced lesions and hence play a crucial role in the stopping of cell division [1–6].

The vision and goal of the nanodosimetric community is to provide a measurable physical quantity, which is better suited to model biological effectiveness than absorbed dose. Nanodosimeter detectors obtain ionization frequency probabilities in nanometric volumes produced by traversing particles of different radiation qualities. Such ionization probability distributions are called ionization cluster size distributions. It is believed that quantities based on the cluster size distribution are helpful to determine the biological effectiveness of a radiation quality. A first cell survival model, which is entirely based on nanodosimetric quantities was successfully introduced last year [7].

Currently four nanodosimeter detectors are in operation. The Ion Counter developed at the Weizmann Institute and in collaboration with Loma Linda University, which is now located at the Physikalisch-Technische Bundesanstalt in Braunschweig (PTB) [8,9], the Jet Counter at the National Centre for Nuclear Research (NCBJ) [10] in Poland, the Startrack Counter [11,12] installed at the Legnaro National Laboratories of the Italian Institute of Nuclear Physics (INFN-LNL) and the FIRE (Frequency of Ion REgistration) nanodosimeter detector at University of Zurich (UZH). The FIRE detector is the successor of TIDE (Track Imaging Detector) initially designed by Vladimir Bashkirov and Reinhard Schulte at Loma Linda University to measure the ionization component of the track structure over an arbitrary long track segment in a low pressure gas. TIDE was further developed by Casiraghi at Loma Linda University, at the Paul Scherrer Institute (PSI) in Villigen, Switzerland and at the Gaseous Detector Development Laboratory at CERN [13–16]. To obtain the ionization cluster size distribution the Jet Counter, the Ion Counter, and the FIRE nanodosimeter measure the positive ions, whereas the Startrack Counter measures electrons. All four nanodosimeters take measurements in gaseous media and...
all of these detectors, except the FIRE detector, are large-sized and not portable. Additionally, some discrepancies between experimentally obtained cluster size distributions with the different detectors exist [17, 18]. However, a comparison of cluster sizes obtained by different detectors is difficult since they measure the number of ionizations in different volume sizes. Nevertheless, it has been shown that the cumulative probabilities \( F_1, F_2 \) and \( F_1 \) as a function of the first moment \( M_1 \) are independent of detector type, volume size and radiation quality [18].

Here we report on a further development of the track imaging detector (TIDe) by using new detector materials with a single sensitive volume and a novel data acquisition system. Extensive characterization measurements taken with the compact and portable FIRE nanodosimeter, such as the number of detected ions per alpha particle, the charge per signal, ion arrival time, and the dark counts, i.e. signals registered when the alpha particle source was closed, are presented. In addition, an investigation of the influence of two different dielectric materials on various measurement parameters is reported. First measurements of complete cluster size distributions produced by 5 MeV alpha particles were reported elsewhere [19].

2. Methods

2.1. Principal of operation

The goal of the FIRE nanodosimeter is to measure the ionization yield produced by charged particles above the hole within the dielectric plate. Inspired by the same concept as the Gas Electron Multiplier, but adapted to low pressure, the FIRE nanodosimeter consist of a dielectric plate with one hole. The electrical field lines of characteristic settings of the potentials to the drift anode and cathode are shown in Fig. 1. A detailed sketch of the experimental set-up is shown in Fig. 2. A charged particle, whose ionization cluster size distribution is to be determined, produces ionizations in the gas volume below the hole. The positive ions drift along the field lines towards the hole. The large potential difference between the cathode and the readout electrode as well as between the cathode and the drift electrode, creates a high field strength inside the hole. The ions are accelerated and acquire sufficient energy from the accelerating field to create impact ionizations with the molecules of the gas. Electrons created in this way will be accelerated in the opposite direction, gain even more energy and ionize the gas further. The resulting secondary electrons produce tertiary electrons and so on. Consequently, an avalanche is formed which is limited in space by the walls of the dielectric plate. A sizeable fraction of the electron avalanche will leave the hole and will be collected by the readout electrode. The signal on the readout is only created by electrons and not by positive ions.

It is well known that charges accumulate on the surface of dielectric materials in gas detectors [20–22]. This is known as the charge-up effect and it usually affects the electric field and hence the performance of the detector, in particular its dead time and efficiency. In the FIRE detector positive ions produced inside the hole will more likely attach to the wall closer to the cathode and electrons will attach to the wall closer to the opening of the channel due to their respective charges. This will produce an electric field opposing the field produced by the voltages of the anode and cathode. Therefore, the effective field strength inside the hole will be reduced and the detector becomes less sensitive. As the two tested detector materials show different resistivities a different charge-up behavior is expected.

The cathode consists of a resistive material to prevent discharges. The positive gas ions accumulate on the surface of the resistive cathode and weaken the electric field strength inside the hole.

2.2. Detector set-up

The detector is composed of a dielectric plate with one centered hole, which is inserted into the lid of a low pressure chamber (see a sketch of the set-up in Fig. 2 and a picture of the chamber in Fig. 3). Two materials for the dielectric plate were investigated: A ceramic and a glass-reinforced epoxy laminate (EM 370-5, Elite Material Co., Ltd., Taoyuan City 32849, Taiwan [23]). The ceramic consists mainly of zirconium oxide (\( \text{ZrO}_2 \)) and up to 4% Yttrium oxide (\( \text{Y}_2\text{O}_3 \)) and has a resistivity in the order of \( 10^{10} \, \text{Ωcm} \) at room temperature [24]. The glass-reinforced epoxy laminate has a resistivity of \( \geq 10^{15} \, \text{Ωcm} \) and the surface resistivity is greater than \( 10^{15} \, \text{Ωcm} \) (resistivities were specified by the manufacturer). Its relative permittivity is 4.5. Several dielectric plates with different hole diameters were produced at the workshop at CERN and then further modified by the authors. The thickness of these dielectric plates is 10 mm and hence this was also the length of the hole channel. A thickness of 10 mm was chosen on the basis of measurements taken by Casiraghi et al. who investigated the performance with different thicknesses and showed increased performance with increasing thickness [15]. A low-resistive silicate glass produced by Wang et al. [25] with a resistivity in the order of \( 10^{10} \, \text{Ωcm} \) is placed on top of the dielectric plate. It is sealed with a malleable plastic sealant mass based on synthetic rubber (Teroson Terostat IX; Henkel AG & Co. KGaA, Henkelstrasse 67, 40589 Düsseldorf, Germany). Carbon- and copper-tapes are put on top of the glass. A high voltage cable is soldered on to the top of the copper tape.

The bottom side of the dielectric plate is covered with copper. One copper section, directly around the hole, functioned as the readout electrode. The remaining area around the readout electrode is also covered with copper and connected to ground in order to obtain regular electric field shapes (see Fig. 4). The copper cladding in case of the EM dielectric plate is about 50 μm thick and the rim around the hole is in the order of 20 μm. In case of the ceramic dielectric plate, a copper tape was manually attached to the bottom of the dielectric plate and hence exact measurements of the rim were not performed.

Three different epoxy laminate plates were manufactured at the CERN workshop with 1 mm, 1.5 mm and 2 mm hole diameters.

Inside the low-pressure chamber, a collimated alpha source is placed 11 mm below the dielectric plate in order to produce ionizations inside the sensitive volume. Moreover, a copper anode is mounted 22 mm below the dielectric plate. A surface barrier detector is positioned opposite to the alpha source. It detects all alpha particles, which traverse through the volume below the hole in the dielectric plate (see Fig. 2).

An americium-241 alpha source with a maximum energy of approximately 4.7 MeV is used. The activity of the source is 11.1 MBq±3.3 MBq. With the current collimation configuration, this activity translates to
A sketch of the experimental set-up is shown. The dielectric plate with a hole is inserted in the lid of the aluminum chamber which is filled with a low-pressure propane gas. A collimated americium-241 source emits alpha particles which ionize the gas molecules. The alpha particles are detected with a surface barrier detector (SB detector). The positive ions drift towards the hole where they produce impact-ionizations. This creates an electron avalanche, which is detected by the readout electrode.

Fig. 3. Top view of the low pressure chamber.

Fig. 4. A picture of the FIRE nanodosimeter is shown. Between the two collimators is a scattering filter and together they provide a well collimated beam. The surface barrier detector (SBD) triggers the acquisition window when it detects an alpha particle. A steel slab can be moved in front of the alpha particle beam to block it (e.g. for dark rate measurements). This steel slab can be seen in the lower left corner where a picture of the alpha source mount is shown (including the first collimator) when it is disconnected from the rest of the beamline.

an alpha particle frequency registered in the surface barrier detector of about 10 Hz.

A low pressure is held constant inside the measuring chamber. For these measurements, a pressure range of 0.5 Torr to 2.5 Torr was used. The low pressure allows to measure cluster size distributions in millimetric instead of nanometric dimensions because they can be scaled to nanometric dimensions in liquid water. Propane gas is used as a medium as it has been shown that in propane the mean free path, the
spectral distribution and the energy degradation of secondary electrons are very similar to liquid water [26,27].

2.3. Data acquisition

Whenever an alpha particle traverses the sensitive volume, it is absorbed by a silicon surface barrier detector which triggers a registration window during which counts of signals per alpha particle are stored electronically by a field programmable gate array (FPGA). In addition, the number of dark counts are measured after every measurement. Dark counts are defined as the recorded signal counts when the americium source is closed, i.e. when the gas is not ionized by the alpha particles. A magnet allows to move a slab of steel in front of the alpha particle source in order to block the alpha particle beam from outside the low pressure chamber. The FPGA requires a trigger signal to start the data acquisition. In this case, the trigger signal is delivered by a waveform function generator. The dark count consists of noise and ions created by cosmic rays. The mean number of ions is determined by the subtraction of the dark count from the signal count. Moreover, the alpha particle detection efficiency was measured as well. It is defined as the percentage of alpha particles which traverse the measuring volume and produce at least one recorded signal. In addition, ion arrival times relative to the alpha particles arrival in the surface barrier detector are recorded. Charge measurements are not yet stored digitally and are approximated by the full width at half maximum of the signal times its amplitude.

3. Results

The high cathode voltage has a negative polarity. In the following, the absolute voltage is given for better readability. If no errorbars are indicated in the figures, the statistical error was smaller than the symbols.

3.1. Glass-reinforced epoxy laminate (EM)

3.1.1. Characteristic curve: Cathode voltage

Pressure comparison. The mean number of measured ions per alpha particle as a function of applied cathode voltage are shown for 1.0 Torr, 1.5 Torr and 2.0 Torr in Fig. 5. At all three pressure settings, the mean number of ions increases with increasing voltage until a maximum is reached and for higher voltages it decreases again. The mean number of ions was consistently larger at higher pressure.

In Fig. 6 the corresponding mean dark counts per trigger window are shown. The mean dark count is constant up to 1500 V and increases for higher cathode voltages. The mean dark counts below 1500 V are at least 800 times smaller than the recorded ion counts. The highest number of dark counts was registered at 2500 V and 1 Torr. This corresponds to the lowest signal to dark count ratio of about 20. At lower pressure the dark rate will increase already at a smaller acceleration voltage than at higher pressures.

The mean charge per signal as a function of high acceleration voltage is shown in Fig. 7. The mean charge increased with increasing applied acceleration voltage until a plateau is reached. In addition, it can be observed that the charge per signal is larger at higher pressure.
Fig. 7. The dependence of the mean charge per signal on the applied cathode voltage to the cathode is shown for three pressure values (1.0 Torr, 1.5 Torr and 2.0 Torr). The EM dielectric plate with the hole diameter of 1.5 mm was used. The anode voltage was set to 10 V.

Fig. 8. Mean arrival times as a function of applied cathode voltage for three pressures values (1.0 Torr, 1.5 Torr and 2.0 Torr) are shown. The EM dielectric plate with the hole diameter of 1.5 mm was used. The anode voltage was set to 10 V.

In Fig. 8 the mean ion arrival time as a function of cathode voltage to the cathode is shown. At 2 Torr the mean ion arrival time increases with increasing cathode voltage. But above 1500 V the increase in time is small. At 1.5 Torr the mean arrival time increases with increasing acceleration voltage up to 1800 V. For higher acceleration voltages a slight decrease is observed. The mean arrival time at 1 Torr has a minimum at 1000 V. For higher voltages it is monotonically increasing in the measured voltage range.

In Fig. 9 the dependency on cathode voltage of the alpha particle detection efficiency is shown. As can be seen, the higher the pressure is, the higher is the alpha particle detection efficiency. Exceptions to this are the efficiencies obtained at 1500 V, where the efficiency at 1.5 Torr is the lowest. Additionally, it can be seen that the alpha particle detection efficiency increases with the applied cathode voltage until a maximum is reached and then the alpha particle detection efficiency decreases again.

Hole diameter comparison. The mean number of ions detected per alpha particle as a function of acceleration voltage is shown in Fig. 10. Results are shown for measurements taken with three different hole diameters, namely 1.0 mm, 1.5 mm, and 2.0 mm. The pressure was set to 1 Torr and the voltage applied to the anode was 10 V. The mean number of ions increases with cathode voltage until a maximum is reached and then the mean number of ions decreases again. The larger the hole diameter, the larger the measured mean number of ions.

The mean number of dark counts per trigger window, corresponding to the mean number of ions reported in Fig. 10, is shown in Fig. 11. Up to a cathode voltage of 1200 V the mean number of dark counts is rather constant and then the mean dark count increases with higher voltages. The mean number of dark counts increased with the 2 mm hole diameter at a lower cathode voltage than compared to the other two dielectric plates. However, the mean number of dark counts increased faster for the measurements taken with the 1.0 mm hole diameter than with the 1.5 mm diameter.

In Fig. 12 the corresponding mean arrival times as a function of acceleration voltage are shown. The mean arrival time increases with increasing acceleration voltage and is also greater for larger hole diameters. Exceptions were observed at 900 V and 1000 V, where the mean arrival times measured with the 1 mm hole diameter were similar to the arrival times obtained with the 1.5 mm hole diameter. The difference between the mean arrival times for the three different hole diameters is smaller for lower voltage applied to the cathode.

3.1.2. Characteristic curve: Drift voltage

Pressure comparison. In Fig. 13 the dependence of the mean number of detected ions per alpha particle on the applied drift voltage is shown. The dependency on drift voltage was investigated at 1.0, 1.5 and 2.0 Torr. As can be seen the mean number of ions per alpha particle is largest at 2 Torr. Moreover, the mean number of ions per alpha particle is decreasing with increasing drift voltage. Except at 1 Torr the mean number of ions per alpha particle is increasing when the drift voltage is increased from 5 V to 6 V.

COMSOL calculations of the electric field for two different voltages to the anode are shown in Fig. 14. The electric field exhibits a funnel-like shape, where the shape is broad in the drift region and narrow in the hole channel. As expected, the shape of the electric field is broader in the drift region, when the anode voltage is lower assuming the voltage to the cathode is kept constant.
Fig. 9. Dependency of the alpha particle detection efficiency on the acceleration voltage for three pressure settings (1.0 Torr, 1.5 Torr and 2.0 Torr) are shown. The EM dielectric plate with the hole diameter of 1.5 mm was used. The anode voltage was set to 10 V.

Fig. 10. Mean number of ions per alpha particle detected with three different hole diameters (1.0 mm, 1.5 mm and 2.0 mm) as a function of acceleration voltage applied to the cathode. Pressure was set to 1 Torr and 10 V were applied to the drift electrode. The material of the dielectric plates was the glass-reinforced epoxy laminate.

Fig. 11. Mean dark counts per trigger window as a function of cathode voltage. Measurements performed at a pressure of 1 Torr and a drift voltage of 10 V. The material of the dielectric plates was the glass-reinforced epoxy laminate.

The mean dark counts per trigger window as a function of applied anode voltage are not shown because it is negligible small and no dependence on drift voltage or pressure was found.

The mean charge per signal as a function of drift voltage obtained at 1.0 Torr, 1.5 Torr and 2.0 Torr is shown in Fig. 15. It can be observed that the mean charge per signal increases with increasing pressure. Moreover, the mean charge per signal does not show a dependency on the applied voltage to the anode.

The corresponding mean arrival time of the ions as a function of drift voltage is shown in Fig. 16. It can be seen that the general trend of the mean arrival time decreases with increasing drift voltage. The arrival time obtained at 2 Torr is greater at all drift voltages. Up to 10 V, the mean arrival times obtained at 1 Torr are greater than the mean arrival time at 1.5 Torr.

In Fig. 17 the mean number of ions per alpha particle as a function of applied drift voltage at a pressure of 1 Torr and acceleration voltages of 1200 V and 1400 V are shown. Additionally, the mean number of ions per alpha particle obtained at a pressure of 0.5 Torr and an acceleration voltage of 1400 V is shown. For each curve a maximum in the mean number of ions per alpha particle can be observed. The mean number of
Fig. 12. Mean arrival times as a function of cathode voltage. The voltage applied to the anode was 10 V and the pressure was 1 Torr. The material of the dielectric plates was the glass-reinforced epoxy laminate.

Fig. 13. Mean number of detected ions per alpha particle as a function of applied drift voltage to the anode for three different pressure settings (1.0 Torr, 1.5 Torr and 2.0 Torr). The cathode voltage was set to 1200 V. The EM dielectric plate with the 1.5 mm hole diameter was used.

Fig. 14. COMSOL calculations of the electric field for different anode voltages and an applied voltage to the cathode of 1200 V. The field line density is not proportional to the field strength.

ions per alpha particle taken at 1 Torr and 1200 V reaches its maximum at an applied drift voltage of 5 V. The maximum mean number of ions in case of 1400 V applied to the cathode and a pressure of 1 Torr is reached at 10 V applied to the anode. The measurement taken at 0.5 Torr reaches the maximum at 20 V. Moreover, the maximum is shifted towards a higher voltage, when the measurements at 1 Torr are compared. Noticeable is the drop in the mean number of ions per alpha particle at low drift voltages at a pressure of 0.5 Torr.

The mean arrival times as a function of drift voltage is shown in Fig. 18. The higher the pressure and the higher the applied voltage to the cathode, the larger the observed mean arrival time of the ions. The arrival time decreases with increasing drift voltage. At 1 Torr and at high drift voltage, the mean arrival time seems to be independent on the acceleration voltage.

Hole diameter comparison. The mean number of detected ions as a function of drift voltage is shown in Fig. 19. Three dielectric plates
Fig. 15. Mean charge per signal as a function of the applied drift voltage to the anode. The EM dielectric plate with the 1.5 mm hole diameter was installed for these measurements. The voltage applied to the cathode was 1200 V.

Fig. 16. Mean arrival time as a function of the applied drift voltage to the anode. The EM dielectric plate with the 1.5 mm hole diameter was installed for these measurements. The voltage applied to the cathode was 1200 V.

Fig. 17. Mean number of detected ions per alpha particle as a function of drift voltage. The dielectric EM plate with the 1.5 mm hole diameter was used. The voltages applied to the cathode were 1200 V and 1400 V.

with hole diameters of 1.0 mm, 1.5 mm and 2.0 mm were used. The mean number of ions per alpha particle decreases with the applied drift voltage. The larger the hole diameter, the larger the mean number of detected ions. For the measurements taken with the 2.0 mm hole diameter, a maximum of mean number of ions can be observed at 8 V to 10 V. The maximum observed mean ions with the 1.5 mm diameter
Fig. 18. Mean arrival time as function of drift voltage. The dielectric EM plate with the 1.5 mm hole diameter was used.

Fig. 19. Mean number of ions per alpha particle as a function of applied voltage to the drift electrode for three different hole diameters (1.0 mm, 1.5 mm and 2.0 mm). Pressure was set to 1 Torr and 1200 V were applied to the cathode. The material of the dielectric plates was the glass-reinforced epoxy laminate.

hole is at 6 V to 8 V, whereas the maximum detected with the 1 mm hole diameter is at 5 V to 6 V. The maximum of mean ions shifted to lower drift voltages with decreasing hole diameter.

COMSOL calculations of the electric field for hole diameters of 1 mm and 2 mm are shown in Fig. 20. The larger the hole diameter, the larger the area below the hole from which electric field lines enter the hole.

The mean charge as a function of drift voltage for the measurements with the three different hole diameters is shown in Fig. 21. The larger the hole diameter, the larger the recorded charge per signal. For the 2 mm hole diameter an increase of charge per signal is observed with increasing drift voltage up to 25 V and then again a decrease at 30 V. For the 1.5 mm hole diameter a slight increase can be seen from 7 V to 8 V and then, for higher drift voltages the mean charge is constant. For the 1 mm hole a maximum is seen at 6 V and then for higher voltages a slight decrease can be observed.

In Fig. 22 the arrival time as a function of drift voltage for the three different hole diameters is shown. The arrival time decreases with increasing drift voltage. In general, the larger the hole diameter is, the longer it takes the ions to arrive. The arrival times of the 2 mm and the 1.5 mm hole are very similar. At 5 V and 6 V the arrival time from the 1.5 mm hole diameter measurement is larger than the arrival time from the 1 mm hole diameter measurement.

3.1.3. Detector measurements at the operation limit

The best spatial water-equivalent resolution of the nanodosimeter can be achieved at the lowest pressure and with the smallest hole diameter. In the FIRE nanodosimeter the dielectric plate with the smallest hole has a diameter of 1 mm and the lowest pressure setting is 0.5 Torr. Measurements taken at these limits of the FIRE nanodosimeter are discussed separately here.

The mean number of ions per alpha particle as a function of cathode voltage detected with the 1.0 mm hole in the dielectric plate is shown in Fig. 23. The cathode voltage was 1200 V and the positive drift voltage applied to the anode was 10 V. It can be seen that the mean number of ions per alpha particle as a function of acceleration voltage at 1 Torr follow a parabola with a maximum at 1400 V. The mean numbers of ions per alpha particle recorded at 0.5 Torr is larger and the maximum seems to be reached at 2100 V. The corresponding mean dark counts per trigger window as a function of cathode voltage are shown in Fig. 24. At 1 Torr the mean number of dark counts is increasing with increasing cathode voltage. The mean number of dark counts at 0.5 Torr is of the same order of magnitude as at 1 Torr.

In Fig. 25 the mean charge per signal as a function of cathode voltage is shown for 0.5 and 1.0 Torr. The trend of the mean charge per signal is increasing with increasing applied cathode voltage. The mean charge per signal is larger at 1 Torr than at 0.5 Torr.

The mean arrival times as a function of cathode voltage are shown in Fig. 26. The fastest arrival times at 1 Torr were observed for 1100 V to 1200 V. For lower and for higher voltages, the mean arrival times increased. The arrival times measured at 0.5 Torr were smaller compared to the arrival times at 1 Torr.
Fig. 20. COMSOL calculations of the electric field for different hole diameters. The applied voltage to the cathode is 1200 V and the voltage applied to the anode is 20 V. The field line density is not proportional to the field strength.

Fig. 21. Mean number of charge per signal as a function of applied voltage to the drift electrode for three different hole diameters (1.0 mm, 1.5 mm, and 2.0 mm). Pressure was set to 1 Torr and 1200 V were applied to the cathode. The horizontal solid line at 89 pC represents the mean charge collected with the 1 mm hole diameter. Dashed lines at 134 pC and 178 pC are scaled with the correspondent hole diameters. The material of the dielectric plates was the glass-reinforced epoxy laminate.

Fig. 22. Mean arrival time as a function of applied voltage to the drift electrode for three different hole diameters (1.0 mm, 1.5 mm, and 2.0 mm). Pressure was set to 1 Torr and 1200 V were applied to the cathode. The material of the dielectric plates was the glass-reinforced epoxy laminate.

All measurements presented showed higher fluctuations at 0.5 Torr. A stable operation of the FIRE nanodosimeter at this low pressure is challenging. It was observed that larger cathode voltages are required at such a low pressure for maximizing the mean number of ions per alpha particle.

3.1.4. Aging effects

Measurements taken at the beginning of a two week lasting experimental run are compared to results taken at the end. In Fig. 27 the mean number of ions per alpha particle as a function of cathode voltage at 2 Torr is shown. As can be seen, more ions were detected in the
Fig. 23. Mean number of ions as a function of cathode voltage measured at 0.5 Torr and 1.0 Torr. The hole diameter of the EM dielectric plate was 1 mm. The anode voltage was set to 10 V.

Fig. 24. Mean number of dark counts as a function of cathode voltage and measured at 0.5 Torr and 1.0 Torr. The hole diameter of the EM dielectric plate was 1 mm. The anode voltage was set to 10 V.

Fig. 25. Mean measured charge per signal as a function of cathode voltage at 0.5 Torr and 1.0 Torr. The hole diameter of the EM dielectric plate was 1 mm. The anode voltage was set to 10 V.

beginning of the measurement compared to the measurements at the end. However, the slope is similar. In both runs, the mean number of ions per alpha particle is increasing with increasing cathode voltage. The measurements taken at the end were performed over a wider range of cathode voltages and it can be observed that a maximum in the mean number of ions per alpha particle is reached at 2000 V. For higher cathode voltages a sharp drop in the mean number of detected ions per alpha particle is observed.

The mean number of dark counts is constant over time but is increasing with increasing cathode voltage, especially at high voltages, as is shown in Fig. 28. The mean charge per signal as a function of cathode voltage is not shown. It was increasing with cathode voltage
Fig. 26. Mean arrival times as a function of cathode voltage measured at 0.5 Torr and 1.0 Torr. The hole diameter of the EM dielectric plate was 1 mm. The anode voltage was set to 10 V.

Fig. 27. The mean number of detected ions per alpha particle as a function of cathode voltage is shown. Hole diameter is 1.5 mm and pressure was set to 2 Torr. The drift voltage to the anode was 10 V. The material of the dielectric plate was the glass-reinforced epoxy laminate.

Fig. 28. The mean number of dark counts as a function of cathode voltage is shown. The hole diameter is 1.5 mm and the pressure was set to 2 Torr. The drift voltage to the anode was 10 V. The material of the dielectric plate was the glass-reinforced epoxy laminate.

up to 2200 V and then it decreased. In the beginning of the experimental run, the charge was only recorded at 1500 V. The mean charge at 1500 V was larger in the beginning of the experimental run compared to the charge measured at the end.

The mean arrival time as a function of cathode voltage measured at the beginning of the experiment and at the end, are shown in Fig. 29. The arrival times are similar but they were slightly faster in the beginning of the experimental run with the exception at 1200 V.

3.1.5. Scaling via pressure setting

Assuming ionizations are created directly by the alpha particle, theory predicts that the mean number of ionizations will be the same
if the mass per area remains the same. That is if the diameter of the sensitive volume is reduced by half and the pressure is doubled, the same mean cluster size distribution is obtained. In Fig. 30 the mean numbers of ions per alpha particle detected with the 1.0 mm hole at 1.0 Torr and with the 2.0 mm hole at 0.5 Torr as a function of cathode voltage are shown. For both settings the mean number of detected ions per alpha particle increases with increasing cathode voltage until a maximum is reached and for higher voltage the mean number of ion decreases. The maximum in mean number of ions per alpha particle is slightly larger for the 2.0 mm hole at 0.5 Torr than for the 1.0 mm hole at 1.0 Torr. The maximum of the mean number of ions per alpha particle is reached at a lower cathode voltage for the 2.0 mm hole.

The corresponding mean charges per signals are shown in Fig. 31. For both settings the mean charge per signal increases with increasing
3.1.6. Ion depositions on glass cathode

After measurements depositions of gas ions could be observed on top of the glass cathode. Some photographs of such depositions are shown in Figs. 33 to 35. The depositions are observed on the glass cathode where the hole was located. After the glass cathode has been rinsed with medical gasoline, some visible marks persist as can be seen in Fig. 35.

3.2. Ceramic (Zirconium Oxide)

3.2.1. Dielectric constant

The dielectric constant of zirconium oxide with a small amount of yttrium oxide is 29 [24]. That of the EM material is 4.5 [23]. Thus, the dielectric constant of the ceramic used is more than 6 times that of the EM material. This difference in the dielectric property results in differences of the electric fields and potentials of the two detector set-ups. In order to quantify the effects, the electric field strengths and potentials were calculated with the multiphysics modeling software COMSOL. Fig. 36 shows the resulting plots of the electric field and potentials for the EM (Fig. 36(a)) and the ceramic dielectric plate (Fig. 36(b)). The electric potential difference when using these two dielectric plates with an anode voltage of 10 V and a cathode voltage of 1200 V is shown in Fig. 37. As can be seen, the absolute value of the electric potential inside the hole of the dielectric plate in the case of the ceramic plate is lower than the electric potential when using the EM plate. The electrical potential difference was calculated along the $z$-axis and is shown in Fig. 38. The difference of the electric potentials inside the hole increases linearly towards the cathode until a maximum is reached very close to the cathode. The maximal difference between the two electric potentials is approximately 180 V. In addition,
the diameter of the field lines going into the hole of the dielectric plate was determined at the level of the traversing alpha particles (i.e. $z = -1.1 \text{ cm}$). In case of the ceramic dielectric plate the diameter of the field lines going into the hole is smaller than in case of the EM dielectric plate. The difference of the two diameters is $0.04 \text{ cm} \pm 0.01 \text{ cm}$ (at $z = -1.1 \text{ cm}$).

### 3.2.2. Efficiency

The mean numbers of detected ions per alpha particle as a function of the applied acceleration voltage to the cathode are shown in Fig. 39. The pressure was set to 1 Torr and the drift voltage applied to the anode was set to 10 V. The alpha detection efficiencies obtained with the ceramic and the EM detector as a function of cathode voltage are shown in Fig. 40. The corresponding mean charges per signal and the arrival times are shown in Figs. 41 and 42, respectively. The measured dark counts per trigger window are shown in Fig. 43.

It can be observed that more ions per alpha particle are measured with the ceramic detector when compared to the EM, although the alpha particle detection efficiency with the ceramic detector is smaller. For a relative comparison of the two detectors the ion detection efficiency $\varepsilon_{\text{ion}}$ (Fig. 39) and the alpha particle detection efficiency $\varepsilon_{\alpha}$ (Fig. 40) can be used. The total ion detection efficiency $\varepsilon$ is then calculated by dividing $\varepsilon_{\text{ion}}$ by the mean number of produced ions per alpha particle $M_1$. The efficiencies are listed in Table 1 for the two different detector materials at a cathode voltage of 1500 V and a drift voltage of 10 V. For measurement of cluster sizes a large ion detection efficiency is essential.

For the determination of the absolute ion detector efficiency it is important to know the number of produced ions per alpha particle. Unfortunately, it is not possible to measure the absolute ion detection efficiency with our current set-up. Therefore, Monte Carlo simulations of 5 MeV alpha particles were carried out in a water sphere with a diameter of 2.5 nm. As a result the mean number of produced ions per alpha particle ($M_1$) was obtained. $M_1$ was determined to be 4.58.

As the exact size of the sensitive volume of the FIRE detector is not known and is pressure dependent, a diameter of 2.5 nm was chosen for this work. A detailed analysis of the number of ions as a function of the size of the sensitive volume is given elsewhere [19]. The determination of the absolute ion detection efficiency is important for the reconstruction of cluster size distributions measured with detectors of limited efficiencies.

### 3.2.3. Cluster size distributions

With the absolute ion detection efficiency, determined in the last section, a Bayesian reconstruction algorithm was applied to transform...
Fig. 37. The electric potential difference when using the EM dielectric plate and the ceramic dielectric plate, as shown in Fig. 36. The black solid line represents the dielectric plate borders. The cathode is located at \( z = 1 \text{ cm} \) and the signal readout at \( z = 0 \text{ cm} \). The voltage applied to the cathode is 1200 V and the voltage applied to the anode is 10 V. The electric potentials are calculated with the multiphysics modeling software COMSOL.

Fig. 38. The electric potential difference on the central axis for the two materials is shown. The voltage applied to the cathode is 1200 V and the voltage applied to the anode is 10 V. The solid blue line shows the electric potential for a dielectric plate made of EM material with a dielectric constant of 4.5. The dashed orange line shows the electric potential for a dielectric plate made of ceramic with a dielectric constant of 29. The dash-dotted red line represents the difference of the electric potentials of the two dielectric plates. The gray area on the \( z \)-axis indicates the location of the dielectric plate in \( z \)-direction. Here, the cathode is located at the right side of dielectric plate (i.e. \( z = 1 \text{ cm} \)) and the anode on the left side at \( z = -2.2 \text{ cm} \). The electric potentials were calculated with the multiphysics modeling software COMSOL.

Fig. 39. Mean number of ions per alpha particle detected with the ceramic plate and the EM plate as a function of cathode voltage. The pressure was set to 1 Torr and the anode voltage to 10 V.

A measured cluster size distribution from the ceramic detector to the predicted one. A new dielectric ceramic plate was used, so that the aging of the detector is negligible (see also the next section on aging of the detector 3.2.4). Details of the reconstruction method can be found.
in [19]. Fig. 44 shows a comparison between the Monte Carlo simulated cluster size distribution, the measured one and the reconstructed cluster size distribution $P_t$ from the measurement.

In Fig. 45 the measured cluster size distributions of the EM and the ceramic detector are compared. It can be observed that the largest cluster size measured is two with the EM detector and ten with the ceramic detector. It is obvious that a reconstruction of the cluster size distribution is hardly possible with the data from the EM detector.

3.2.4. Aging of the detector

The stability of the detector system with time was investigated for the EM detector and ceramic detector in terms of the measurement of the mean ions per alpha particle. It was found that the EM detectors performance did not vary much over time. However, the ceramic detector shows clear signs of aging and a rapid decline in its performance (Fig. 46). After a week of measurements, the measured mean ions per alpha particle decreased from 0.6 to 0.1. After 40 days the detector...
Fig. 43. The mean dark count per trigger window as a function of cathode voltage. The dark count is shown for the ceramic plate and the EM plate. The pressure was set to 1 Torr and the anode voltage to 10 V.

Fig. 44. Bayesian reconstructed cluster size distribution \( P_\nu \) obtained with the ceramic nanodosimeter is shown. The Bayesian reconstruction algorithm was applied to the experimentally obtained cluster size distribution \( P_\mu \) with a detector efficiency of 19.9%. This detector efficiency was previously determined from Monte Carlo simulations. In the Monte Carlo simulations a spherical sensitive volume with a diameter of 2.5 nm is assumed. (For more information on the reconstruction method and for detailed comparisons between reconstructed cluster size distributions with Monte Carlo simulations, see [19]). The pressure was set to 2 Torr, the high voltage to 1500 V and the anode voltage was 10 V.

Source: Reproduced with permission from Vasi et al. [19].

Fig. 45. Measured ions per alpha particle obtained with the EM and the ceramic detector materials. The pressure was set to 2 Torr, the cathode voltage to 1500 V and the anode voltage to 10 V.

was no longer operational and was removed from the gas chamber. A close inspection of the ceramic detector surface and of the wall of the hole showed accumulated depositions, possibly from fragments of the propane gas molecules. This is displayed in Fig. 47.
4. Discussion

4.1. Glass-reinforced epoxy laminate (EM)

4.1.1. Characteristic curve: Cathode voltage

Pressure comparison. The typical behavior of the mean number of detected ions per alpha particle as a function of applied voltage to the cathode, as seen in Fig. 5, can be explained by several physical phenomena. Firstly, the increase of the detected ions per alpha particle with an increasing acceleration voltage can be explained by the higher acquired speed of the ions which subsequently translates into a greater probability for an ion to produce an initial electron–ion pair through impact ionization. The stronger the electric field inside the hole, the higher the energy acquired by the electrons and the ions, resulting in larger and faster avalanches. Electrons are moving very fast in the strong reduced electric field and are neutralized on the readout electrode, while slow ions produce a positive charge cloud.

Secondly, the electric acceleration field is shielded by slow ions. The more charges are produced inside the hole channel, the weaker the electric acceleration field due to the positive charge of the ions. In addition, the electric acceleration field is also shielded by the accumulation of positive ions on top of the low-resistive silicate glass. The shielding of the acceleration field will reduce the efficiency of the detector because additional ions from the sensitive volume drifting into the hole channel will then not acquire enough energy to produce impact-ionizations. The stronger the electric acceleration field, the more charges are produced and hence the longer the electrical field is reduced. A characteristic maximum, which is pressure dependent with a shift of approximately 400 V per Torr was observed (Fig. 5).

The mean number of dark counts for all three measured pressures are in the same order of magnitude. Generally, an increase of dark counts can be seen at higher voltage. The dark counts could come from ionizations produced by background radiation or electron emissions from the walls of the detector or from the surface of the cathode.

The flattening of the mean charge with increasing acceleration voltage seen in Fig. 7 comes either from the lateral limit of the avalanche size which is imposed by the wall of the hole or the accumulation of positive ions on the cathode surface which then reduces the electric field strength.

The detected alpha particle efficiency is almost identical to the mean number of detected ions per alpha particle because not more than two ions per alpha particle are detected. One reason for this is the increased dead time due to the accumulation of positive ions on the cathode and on the wall of the hole channel (charge-up effect).

Hole diameter comparison. The dependence of the mean number of ions per alpha particle on cathode voltage for three different hole diameters was shown in Fig. 10. All three measurement curves exhibit a maximum. The maxima were reached at 1400 V when measured with the 1.0 mm hole diameter, at 1700 V when measured with the 1.5 mm
hole diameter and at 1500 V when measured with the 2.0 mm hole diameter.

A larger hole diameter translates to larger avalanches since more gas molecules are available to produce impact ionizations. However, a plateau is expected when the diameter of the electron avalanche is smaller than the hole diameter and the avalanche is not limited by the walls. The increased positive charges on the cathode will reduce the effective electric field inside the hole for a longer time. When the hole diameter is larger, more positive and negative charges are produced and more particles attach to the wall. Moreover, the surface of the wall is also larger and hence the electric field inside the hole might be more reduced because a stronger electrical field is produced by the charge-up effect which weakens the effective electrical strength. This hypothesis can also be supported by the measured mean arrival times shown in Fig. 12. The arrival time increases with hole diameter, which could be an effect of the increased sensitive volume with larger hole diameter. However, the charge-up effects and the dynamically changing electric field inside the hole could be of importance as well.

4.1.2. Characteristic curve: Drift voltage

Pressure comparison. In Fig. 13 it can be observed that the mean number of ions per alpha particle decreases with increasing voltage applied to the anode. The reason is the decreasing sensitive volume with increasing drift voltage as can be seen in Fig. 14.

As expected, the mean arrival time curves in Fig. 16 show faster ions for increasing drift voltage. The lower the pressure, the faster the arrival times. The reason is that at lower pressure, the ions experience fewer collisions with gas molecules due to an increased mean free path length.

In Fig. 17 it can be seen that an increase in cathode voltage shifted the curve to higher drift voltages. A reason for this could be the changed electric field configuration which changes the size of the sensitive volume. A constant ratio of drift to acceleration voltage preserves the size of the sensitive volume.

As can be seen a shift of the curves at 0.5 Torr towards higher drift voltages can be observed. At low drift voltage and at 0.5 Torr, the mean number of ions is decreased compared to 1 Torr. This is also the case when the electric field configuration is the same. Therefore, a reason could be the increased diffusion at low pressure (0.5 Torr) together with a weak electric field.

As expected, at a lower pressure, decreased arrival times were observed (Fig. 18). The increased arrival time at 1 Torr for a cathode voltage of 1400 V could be due to the increased size of the sensitive volume.

4.1.3. Aging effects of the detector

During a long experimental run a decrease in performance is seen (Fig. 27). In addition, the mean charge per signal was lower at the end of the measurement compared to the beginning (at an applied voltage of 1200 V; not shown).

A reason for this could be the accumulation of depositions on the surface of the glass cathode as seen in Figs. 33 to 35. If these layers of depositions have a high resistivity the performance of the detector could decrease. Some layers can be removed with medical gasoline but markers on the glass are still visible afterwards. Aging of gas detectors because of resistive layers has already been observed in proportional and Geiger counters and in gas electron multipliers [28]. The deposition of insulating layers on electrodes is often attributed to polymerization of organic molecules in the avalanche process [28,29]. Usually, large molecules are formed during polymerization and are either deposited on the glass or react with it and thus induce aging processes [29].

4.1.4. Scaling via pressure setting

If the efficiency does not depend on hole diameter or pressure and if the cluster size distribution does not depend on the contribution of secondary electrons then it would be expected that for a hole diameter of 1 mm and a pressure of 1.0 Torr the mean number of detected ions per alpha particle would be the same as for a hole diameter of 2 mm and a pressure of 0.5 Torr. As can be seen in Fig. 30 the maximum of these two settings are not reached at the same cathode voltage. This is expected since the location of the maximum depends on the energy of the ions and hence is pressure and voltage dependent. However, the maximum numbers of ions per alpha particle are similar. Nevertheless, it can be seen that applying only pressure scaling is not sufficient to explain the difference. It can be concluded that the ion detection efficiency depends on the contribution of secondary electrons or on pressure and/or hole diameter. This could suggest that the impact probability has not yet reached 100% inside the hole and/or that the ion detection efficiency depends on the produced charge inside the hole. As shown in Fig. 31 the mean charge per signal was larger at higher pressure and smaller hole diameter.

It can be concluded that the diameter of the hole has a larger influence on the mean number of ions and on the alpha particle detection efficiency than pressure in the range of 1 Torr to 2 Torr (see Figs. 5, 10, and 30) or drift voltage (see Fig. 19)

From the collection of measurements it can be concluded that the optimal operational parameters for the FIRE nanodetector are a pressure of 1 Torr, a hole diameter of 1.5 mm, a cathode voltage of 1700 V and an anode voltage of 6 V to 8 V.

4.2. Ceramic (Zirconium Oxide)

The impact of the resistivity of two dielectric materials on the efficiency of a compact nanodetector was investigated. The two resistivities differ by six orders of magnitude. According to the manufacturer the zirconium dioxide ceramic has a resistivity in the order of 10^{16} \Omega cm [24] but the resistivity depends strongly on the manufacturing process and could be up to 10^{17} \Omega cm. The resistivity of the EM material is greater than 10^{16} \Omega cm [23].

It was shown that dielectric material properties in a GEM-like detector are of great importance because it impacts the drain of the unavoidable charge-up at the detector walls and thus the dead time and efficiency are affected.

As can be seen in Fig. 39, the mean number of ions per alpha particle increases with cathode voltage until a maximum is reached and then decreases. The reason for the increase is that the initial ions acquire higher energies when the acceleration field is stronger. Ions with higher energy have a greater ionization impact-probability. The decrease of the mean number of ions per alpha particle at higher cathode voltages could come from the increased number of accumulated ions on the surface of the glass cathode and the wall of the hole. A subsequent build-up of a reverse electric field decreases the efficiency. The more ions accumulate, the longer it will take to restore the electric field inside the hole.

The alpha particle detection efficiency obtained with the EM detector has a maximum at 1700 V (see Fig. 40) and strictly decreases for higher voltages. The alpha particle detection efficiency of the ceramic detector does not show such a decline in its efficiency with higher cathode voltage. This could be caused by the more efficient drain of charges in the ceramic detector. The alpha particle detection efficiency at the maximum obtained with the EM detector is greater than the one obtained with the ceramic detector. The reason for the higher alpha particle detection efficiency of the EM detector is not known and has to be investigated further.

The mean charge per signal increases with increasing applied voltage to the cathode (Fig. 41). The reason is that the ions and the electrons inside the hole acquire higher energies and therefore have a higher probability to ionize propane gas molecules. The mean charge
per signal obtained with the ceramic detector at any cathode voltage is larger than the mean charge obtained with the EM detector at the same voltage. This can be explained by a weaker electric field inside the hole in case of the EM detector. The weakening of the electric field could come from the reverse electric field which could be caused by the charge-up effect. It is expected that charges stay longer on the surface of the EM detector compared to the ceramic detector since it has a higher resistivity.

The mean arrival times of the ions obtained with the EM and the ceramic detector increase with increasing cathode voltage (Fig. 42). The applied voltage to the anode was kept constant at 10 V. The mean arrival times obtained with the EM detector are in general larger than the mean arrival times obtained with the ceramic detector. The reason could be that the effective field inside the hole is reduced by the charge-up effect. As the ratio of drift voltage to cathode voltage determines the size of the sensitive volume, the travel times of the ions can be increased.

The mean dark counts obtained with the EM detector are constant up to approximately 1500 V and then increases for higher cathode voltages (see Fig. 43). The mean dark count obtained with the ceramic detector is increasing with increasing cathode voltage and is larger than for the EM detector. A possible explanation for the larger number of dark counts in case of the ceramic plate is that the readout and grounding electrodes were manually attached to the ceramic plate whereas in case of the EM detector they are manufactured and the edges are etched. In previous designs it was recognized that the detectors manufactured at CERN exhibit fewer dark counts [16].

The decline of the performance of the ceramic detector can be explained by its ion conductivity which is characteristic for oxide ceramics [30]. Ion conductivity is often accompanied by electrochemical decomposition. Overall the measurements indicate that a lower resistivity can enhance the performance of the detector with regard to the ion detection efficiency. The increased efficiency allows the measurement of larger clusters and the reconstruction of cluster size distribution. Unfortunately, the zirconium dioxide ceramic is susceptible to aging effects and materials which are less prone to these effects should be investigated. Interesting materials to be investigated further could be SIN/SiC ceramics, which have a tunable resistivity and are used in resistive plate chambers.

5. Conclusion

In summary, extensive measurements in order to characterize the FIRE nanodosimeter were presented. Two dielectric plate materials with different resistivities were investigated. An optimal parameter setting to perform measurements was established. Namely, it was found that measurements should be carried out at a pressure of 1 Torr, with a hole diameter of 1.5 mm, an applied voltage to the cathode of 1700 V and an anode voltage of 6 V to 8 V. Moreover, it was found that the ion detection efficiency with the ceramic dielectric plate setup is increased. This allows reconstructing cluster size distributions. Hence, lower resistive materials have the potential to enhance the performance of the FIRE nanodosimeter. However, it was unfortunately established that the performance of the ceramic dielectric plate decreases with time.

To further improve the FIRE nanodosimeter more materials which are less susceptible to radiation-induced performance degradation should be investigated. Promising materials to replace the oxide ceramic could be SIN/SiC ceramics which are also tunable in their resistivity. Moreover, zirconia ceramics but stabilized with iron oxide are a promising candidate for the cathode since they are tunable over a large range of resistivity and their electrical properties depend on the manufacturing process and treatment and less on the composition. In addition, a lower resistivity of the cathode could enhance the efficiency of the detector further and should be investigated. The use of hydrocarbon based gases should be avoided if possible to prevent the depositions of fragments of gas molecules which result in insulating layers on top of the cathode. An important next step could be the establishment of a constant detection efficiency.

CRediT authorship contribution statement

Fabiano Vasi: Writing - original draft, Software, Conceptualization, Methodology, Investigation. Irina Kempf: Conceptualization, Methodology, Investigation, Software, Writing - review & editing. Jürgen Besserer: Conceptualization, Manufacturing. Uwe Schneider: Conceptualization, Methodology, Writing - review & editing, Supervision. The first two authors contributed equally to this work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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