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Modelling of fission chambers in current mode—Analytical approach

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Abstract

A comprehensive theoretical model is proposed to explain the functioning of fission chambers operated in current mode, even in very high neutron fluxes. The calibration curves are calculated as a function of basic physical parameters as fission rate, gas pressure and geometry of the chambers. The output current at saturation is precisely calculated, as well as the maximum voltage to be applied in order to avoid avalanche phenomena. The electric field distortion due to the space charge phenomena is also estimated. Within this model, the characteristic responses of fission chambers are correctly reproduced, in agreement with the experience feedback obtained at the ILL/Grenoble High-Flux Reactor.
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1. Introduction

Fission ionization chambers are widely used as neutron monitors in irradiating environments such as nuclear reactors, accelerators and medical facilities. They can be used in pulse mode, where each electronic pulse induced by a nuclear fission is counted event by event. Nevertheless, in high neutron fluxes (above $10^{14}\,\mathrm{n\,cm^{-2}\,s^{-1}}$), the pulse pile-up induced by the high fission rate requires a current mode acquisition, where each single event is not anymore individualized.

In order to carry out on-line measurements of transmutation rates of actinides at the Mini-Inca and Megapie installations [1–6], we have recently developed[1] subminiature cylindrical fission chambers designed to stand high temperatures and neutron fluxes up to several $10^{15}\,\mathrm{n\,cm^{-2}\,s^{-1}}$. Beside their use for nuclear waste transmutation studies, these detectors are useful tools for in-core neutron flux diagnostics of Generation-IV nuclear systems.

After several experiments in high neutron fluxes of about $10^{15}\,\mathrm{n\,cm^{-2}\,s^{-1}}$, we have observed that the responses of the chambers as a function of the applied voltage, namely the calibration curves, are perturbed. The shapes of the calibration curves differ significantly from those obtained during irradiation in neutron fluxes one order of magnitude lower. We have experimentally noticed that the pressure of the filling gas and the geometries of electrodes have a strong influence on the responses of the detectors, with differences that are accentuated in high-intensity neutron fluxes.

In order to have a clear understanding of the observed phenomena, we have developed an analytical model to study and predict the evolution of the calibration curves as a function of different physical parameters, as gas pressure, gas composition, applied voltage, during various conditions of irradiation, from low to high intensity neutron fluxes.

This approach is described in the present paper. In the first part, the basic equations used to model the functioning

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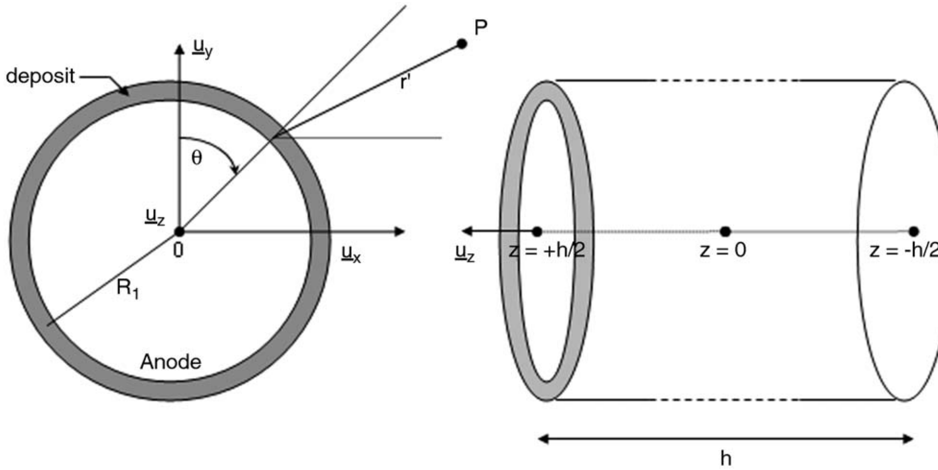

Fig. 1. Scheme of an anode and its deposit.

of fission chambers in current mode are detailed. In a second part, this theoretical framework is applied to the calculation of the calibration curves.

2. Modelling of fission chambers

Cylindrical fission chambers are made of two coaxial electrodes (anode and cathode) separated by a filling gas, as shown in Fig. 5. The anode is usually coated with a fissile element. Under irradiation, neutrons induce fission reactions inside the deposit and high energy fission products (about 90 MeV/each on average for ^{235}U) are emitted in opposite directions. Thus, one is absorbed in the anode while the second crosses the inter-electrode space, ionizing the filling gas on its path and consequently generating a high number of electron–ion pairs. When a voltage is applied, an electric field is generated between the two electrodes, involving a migration of charges. The collected charges are responsible for the creation of an electric current. The layout of this current according to the voltage applied gives a characteristic curve, know as the calibration curve.

In the following, we will consider a standard cylindrical fission chamber with a 98.5% pure ^{235}U deposit (as CFUT-C3[2] chambers used in the framework of the Mini-Inca and Megapie projects (see Fig. 5)).

2.1. Calculation of the charge pair density created by the fission products

In this section, we will evaluate the density N of electron–ion pairs created per unit of time by the fission products in the inter-electrode space. To simplify our calculations, we note $N_{\rm fst}$, the number of fission products released per second and per unit of area at the anode. In cylindrical geometry, one can obtain

$$N_{\rm fst} = \frac{\tau_{\rm f}}{2\pi R_1 h} \tag{2.1}$$

where h is the length of the deposit which partially covers the anode (see Fig. 1 for the notations). R_1 is the anode radius. $\tau_{\rm f}$ is the fission rate, i.e. the number of fissions that take place inside the deposit per unit of time. Let us also note $X(d)$, the average number of pairs created by a fission product per unit of length travelled in the gas. X depends on the distance d covered by the fission product in the inter-electrode space. A first approximation consists in supposing that all the fission products leave the anode with a purely radial speed $\underline{v}$. In cylindrical coordinates, $\underline{v}$ can be written $v_r\underline{u}_r + v_q\,\underline{u} + v_z\underline{u}_z$. Consequently, this assumption fixes to zero the components v_θ and v_z. Within this simplified framework, one can obtain an expression for N that depends only on the r coordinate and that can be written

$$N(r) = \frac{N_{\rm fst} R_1 X(r')}{r} \tag{2.2}$$

with $r' = r - R_1$.

A second approach, developed by Poujade and Lebrun [7], consists in assuming that all fission products leave the deposit perpendicularly to the anode axis. The velocity component v_z is thus fixed to zero and the authors have shown that N depends once more only on r and can be written

$$N(r) = \int_{-\arccos(R_1/r)}^{\arccos(R_1/r)} \frac{N_{\rm fst}}{\pi}\, X(r')\, \frac{R_1(r\cos(\theta) - R_1)}{r^2 + R_1^2 - 2rR_1\cos(\theta)}\,{\rm d}\theta \tag{2.3}$$

with $r' = \sqrt{R_1^2 + r^2 - 2rR_1\cos(\theta)}$.

If the distance d covered by a fission product is small as compared to its mean free path, $X(d)$ remains about constant all along the trajectory. Thus we have $X(d) \approx X_0$. Within this framework (2.3) integral can be calculated and

[2] CFUT-C3 chambers are manufactured by the PHOTONIS Company.

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