Nuclear Instruments and Methods in Physics Research A 836 (2016) 61–66

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Absolute determination of radiation bursts and of proportional counters space charge effect through the influence method

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ARTICLE INFO

Article history:
Received 22 June 2016
Received in revised form
8 July 2016
Accepted 12 July 2016
Available online 14 July 2016

Keywords:
Neutron burst measurements
Absolute measurement
Particle flux determination
Source calibration
Detector efficiency
Influence method

ABSTRACT

When proportional counters are employed in charge integration mode to determine the magnitude of a radiation pulse, so intense that individual detection events take place in a time too short to produce individual output pulses, mostly in pulsed neutron sources, the strong build-up of positive space charge reduces the electric multiplication factor of the proportional detector. Under such conditions the ensuing measurement underestimates the amount of radiation that interacted with the detector. If the geometric characteristics, the filling gas pressure and the voltage applied to that detector are known, it becomes possible to apply an analytical correction method to the measurement.

In this article we present a method that allows to determine the absolute value of the detected radiation burst without the need to know the characteristics of the employed detectors. It is necessary to employ more than one detector, taking advantage of the Influence Method.

The “Influence Method” is conceived for the absolute determination of a nuclear particle flux in the absence of known detector efficiency and without the need to register coincidences of any kind. This method exploits the influence of the presence of one detector in the count rate of another detector, when they are placed one behind the other and define statistical estimators for the absolute number of incident particles and for the efficiency (Rios and Mayer, 2015 [1,2]). Its practical implementation in the measurement of a moderated neutron flux arising from an isotopic neutron source was exemplified in (Rios and Mayer, 2016 [3]) and the extension for multiple detectors in (Rios and Mayer 2016 [4]).

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1. Introduction

When proportional counters are applied to the characterization of intense radiation fields, the great amount of detection interactions generates an important positive space charge left behind by the much faster electrons. This reduces the multiplication factor applied to the original number of primary electrons. If the detector is employed as a “counter”, some pulses of diminished amplitude may not be counted due to the presence of a discriminator, thus the counting may be underestimated. If, instead, the detector is employed in the charge integration mode [5], the overall registered charge will underestimate the magnitude of the detected radiation burst.

An analytic correction method [6] allows to evaluate the electron multiplication reduction and the ensuing effect in the measurement as a function of the collected charge. This method was applied to correct measurements from the LUPIN detector carried out at the HiRadMat Facility at CERN [7], also at the Helmholtz-Zentrum Berlin für Materialien und Energie GmbH(HZB) cyclotron and at the “Elettra Sincrotrone Trieste” (ELETTRA), Italy [8]. A detail of its application appears in a PhD theses on “Development of advanced radiation monitors for pulsed neutron fields” [9]. In order to apply the analytic model it is necessary to know the geometrical characteristics of the detector, the filling gas pressure and the applied high voltage bias.

For the interest of the current work, it is relevant to mention the recent publication of the so called “Influence Method” [1,2]. It was conceived for the absolute determination of a nuclear particle flux without the need to know the detection efficiency and without the need to register coincidences of any kind. The “Influence Method” was initially conceived using two detectors with equal efficiency placed one after the other and considering the number of particles ($\boldsymbol{n}$) falling upon the detector to be a constant during the counting time. This is the case where you want to measure a single event that generates $\boldsymbol{n_0}$ particles, such as a single burst of a Plasma Focus, a pulse of a Z-pinch experiment, an experiment of inertial confinent fusion (ICF), etc.

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http://dx.doi.org/10.1016/j.nima.2016.07.022
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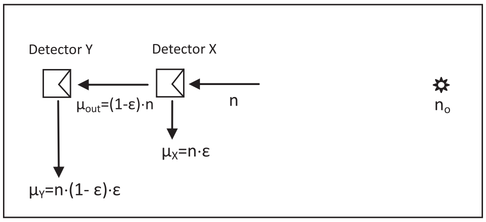

Fig. 1. Original measurement array scheme proposed by the "Influence Method".

Let, in the simplest case, two detectors with the same efficiency ε, be placed one behind the other at a certain distance from the radiation source as schematized in Fig. 1. The number of particles counted by detector X is an aleatory variable ($\boldsymbol{X}$) whose distribution is a binomial of parameters $\boldsymbol{n}$ and $\boldsymbol{\varepsilon}$ ($X \sim Bi(n,\varepsilon)$). In the proposed scheme, particles not detected at X ($X_{out}=n-X$) impinge on detector Y. Thus, the number of those particles detected by Y are an aleatory variable ($\boldsymbol{Y}$) whose distribution is also a binomial of parameters $\boldsymbol{n}$ and $\epsilon\cdot(1-\epsilon)=\epsilon\cdot q$ ($\boldsymbol{Y} \sim Bi(n,\varepsilon q)$ demostrated in [1]), where $q=(1-\varepsilon)$ represents the probability of not being detected by X. Of course, consideration of the cases where particles are removed from the beam by scattering in the first detector, without producing valid counts, the treatment of the case where the efficiency is an energy dependant function and, also, the natural possibility that both detectors do not possess the same efficiency, are taken into account by further refinements. But, for the sake of clarity, let us skip these refinements and look into the basic scheme of the method.

This scheme can be interpreted understanding that the sample of the second variable is influenced by the first one, for which reason we call it the "Influence Method". This influence manifests itself through the correlation between X and Y. Within this scheme we define an estimator for the population and an estimator for the efficiency as,

$$\hat{n}=\frac{X^2}{X-Y} \qquad \hat{\varepsilon}=\frac{X-Y}{X}$$

The original idea has been that the problem to be solved had two unknowns ($\boldsymbol{n}$, $\boldsymbol{\varepsilon}$), so, two magnitudes needed to be measured in order to obtain two results. The materialization of its solution is to place two very similar detectors, one close behind the other, with the characteristic that every particle counted is removed from the beam (not like with proton recoil detectors). Thus, two equations allow estimators for the unknown parameters to be determined.

This idea can also be applied for the case of completely piled up events (burst mode) with ensuing diminishing of electron multiplication due to accumulated positive ion charge. If the number of incident particles ($\boldsymbol{n}$), the efficiency of the detectors ($\boldsymbol{\varepsilon}$) and the positive ion self shielding constant are not known (where it will be later demonstrated that the self shielding can be represented by a parameter $\boldsymbol{A}$), the problem of three unknowns can be solved by the introduction of a third detector, defining statistical estimators for all three variables. Of course, these are detectors considerably transparent for the implied radiations, as it very often happens with neutron detection but not with charged particles.

In Section 2 the solution with three detectors will be developed and Section 3 will deal with the possibility of utilizing only two detectors whenever the efficiency has been obtained in a previous determination. It must be mentioned here that the efficiency is quite insensitive to the space charge accumulated in the burst mode, given the fact that no discriminator is present for such application, for which reason an efficiency determination in the "counter" mode, counting individual pulses with a very low discrimination level, can be useful when applying the two detector burst mode scheme.

2. Estimation with three detectors

2.1. Space charge model

To be realistic, let us consider the situation where the Influence Method will most probably be applied, which is neutron measurements. The number of neutrons deduced from the total electric charge collected after a neutron burst, will be underestimated due to the diminished electron multiplication inside each detector tube, caused by the positive space charge accumulation in the active volume. The diminished gas multiplication after N_i neutron interactions with the detector is [6],

$$\frac{M'}{M}=\frac{\exp\left[-\frac{V}{B}\cdot\ln\left(\frac{V}{C}\right)\right]}{\exp\left[-\frac{V}{B}\cdot\ln\left(\frac{V}{C}\right)\right]+\frac{D}{B}\cdot N_i\cdot\left[1+\ln\left(\frac{V}{C}\right)\right]} \tag{1}$$

where V is the high voltage bias applied to the detector and,

$$B=\frac{\ln\,(b/a)\cdot\Delta V}{\ln 2} \tag{2a}$$

$$C=K\cdot p\cdot a\cdot\ln(b/a) \tag{2b}$$

$$D=\frac{E}{W}\cdot\frac{eb^2}{Vol\cdot 4\varepsilon_o} \tag{2c}$$

where.

a: anode wire radius.

b: cathode inner radius.

ΔV and K are two empirical fitting parameters for the Diethorn expression [11].

p: filling gas pressure.

E: energy of the detection reaction (764 keV for ^{3}He).

W: energy necessary to create an ion-electron pair in the gas.

Vol: Volume where space charge is deposited.

2.2. Estimation of parameters

Eq. (1) can be interpreted as the factor by which the radiation count diminishes due to electric field shielding by positive charge accumulation and it is easy to show that it can be written as

$$F=\frac{M'}{M}=\frac{1}{1+N_i/A} \tag{3}$$

where N_i are neutrons falling upon the detector and $\boldsymbol{A}$ is a constant dependent on the applied voltage, pressure and dimensions. Its analytic expression may be deduced from Eq. (1). Parameter $\boldsymbol{A}$ so defined represents the number of neutrons that having interacted with the detector, reduces the counting to half that number.

Thus, if X are the neutrons which interact with the detector, due to the self shielding, what will really be measured is

$$X_M=F\cdot X=\frac{X}{1+X/A} \tag{4}$$

where X is still an aleatory variable ($\boldsymbol{X}$) whose distribution is a binomial of parameters $\boldsymbol{n}$ and $\boldsymbol{\varepsilon}$ ($X \sim Bi(n,\varepsilon)$). Given the fact that the electric shielding, modeled through Eq. (3), is dependent only on the characteristics of the detector, then parameter $\boldsymbol{A}$ is the same for all similar detectors and affects with the same functional form the aleatory variables which represent the measured count rates as shown in Table 1.

Then, by means of the Influence Method, as there are three unknown parameters ($\boldsymbol{n}$, $\boldsymbol{\varepsilon}$, $\boldsymbol{A}$), it will be necessary to count with three detectors, one behind the other as shown in Fig. 2.

Table 1 exhibits the variables that are measured under the

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