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A wide dynamic range BF_3 neutron monitor with front-end electronics based on a logarithmic amplifier

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ABSTRACT

This paper describes a wide dynamic range neutron monitor based on a BF_3 neutron detector. The detector is used in current mode, and front-end electronics based on a logarithmic amplifier are used in order to have a measurement capability ranging over many orders of magnitude.

The system has been calibrated at the Polytechnic of Milan, CESNEF, with an AmBe neutron source, and has been tested in a pulsed field at the PUNITA facility at JRC, Ispra.

The detector has achieved a dynamic range of over 6 orders of magnitude, being able to measure single neutron pulses and showing saturation-free response for a reaction rate up to $10^6\ s^{-1}$. It has also proved effective in measuring the PUNITA facility pulse integral fluence.

1. Introduction and aim

The detector described here has been developed in order to work in pulsed or very intense neutron fields.

The detector specifications have been defined in reference to beam loss monitoring in hadrontherapy accelerators [1].

Hadrontherapy accelerators usually accelerate heavy ions (such as ^{12}C) to energies up to 400 MeV/u, in bunches with a population up to 10^9 ions, and with a typical frequency of 0.5 Hz.

For both beam diagnostics and radiation protection reasons, it is particularly important to know, for each acceleration cycle, how much of the beam has been lost, the position along the accelerator, and when during the acceleration cycle this occurred.

The beam loss monitoring problem has been solved in many plants with several solutions, many of which focused on secondary radiation detection.

Detectors of secondary photons or electrons are often used in high energy and high current hadron accelerators, [2–5], for personnel radiation protection and machine damage protection.

Since the sixties, [6] plastic scintillators with PMTs in current mode coupled with a logarithmic amplifier have been used to estimate the photon contribution associated with the neutron dose rate due to beam loss in some fixed positions along the beam line for personnel protection.

A particular solution has been found at the Tevatron [4], where the photon flux is detected with argon ionization chambers in current mode connected to a log-integrating amplifier, with a time constant of 60 ms.

Due to the low currents and energies that are used in hadrontherapy plants, fast and intermediate neutrons are the only component of the secondary radiation that can pass through the machine structural materials (such as magnets or mechanical supports), can easily be detected and can provide a quantitative information about the number of lost particles.

The need is for a neutron detector with a wide dynamic range and capable of withstanding very high instantaneous neutron fluxes with little or no saturation and still sensitive to much lower fluxes. The former occurs when all of the beam is lost in a single impact, and the latter when much less of the beam is lost (e.g., 1% of the beam is lost along the spill over a one-second time period). It is worth pointing out that in this kind of measurement, the specifications are more focused on the wide dynamic range and fast response than on precision.

In the event of a sudden beam loss, the neutron fluence at 1 m from the interaction point can be as high as $10^5\ n/cm^2$[7]. If the neutron pulse impinges on a detector made of a BF_3 proportional counter inside a 10 cm radius polyethylene moderator, thermalization will occur and result in a thermal neutron population with a life time of a few tens of microseconds. During this time, a rate of tens of millions reactions per second is sustained even inside smaller commercially available tubes.

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This reaction rate cannot be handled by pulse-operated proportional counters, which typically have a pulse shaping time in the order of 1 μs [8], and that are completely saturated at these pulse rates.

On the other hand, in the case of a small and diluted loss, the reaction rate can be as low as 10^2 pulses per second, thus requiring a single pulse recognition above the background.

These kind of problems are generally faced in reactor control systems, where they are generally solved using at least three kinds of monitors for different reactor power ranges [9–11]. Ionization chambers or boron lined detectors are often used in current mode for reactor period control [12,9] and are read with a logarithmic amplifier, thus obtaining a dynamic range up to 8 orders of magnitude. This solution cannot be directly applied to the beam loss monitoring problem for an hadrontherapy plant due to time scale incompatibility. The electronics for reactor control are designed for very slow time phenomena [13], because the reactor period is generally slower than a few tens of seconds [9], while in an hadrontherapy accelerator in case of a sudden loss of the beam the whole pulses is detected in a few hundred microseconds. To address this problem, readout electronics and a new data treatment method for a BF_3 tube coupled with a logarithmic amplifier have been developed, and the detector has been tested at the PUNITA facility at the Joint Research Centre where instantaneous thermal fluxes up to 10^5 n/s cm^2 can be reached.

2. Detector layout

In this work a Centronic® BF_3 tube has been used as a neutron monitor. It is filled with 70 cmHg pressure gas, and has a 25.4 mm diameter and a 310 mm active length, Its sensitivity, as given by the supplier, is S=12.5 cp/(n/cm^2).The current signal generated by the reactions inside the tube is treated by the front end electronics containing the logarithmic amplifier (LogAmp). The general layout is shown in Fig. 1.

(n,α) reactions on ^{10}B create an average charge C that can be calculated as

$$C = \frac{Q \cdot M}{w \cdot e} \tag{1}$$

where Q is the average energy released in the gas by the reaction, M the effective multiplication inside the gas, w the mean ionization energy, and e the elementary charge.

When the tube is exposed to a thermal neutrons beam of fluence rate $\Phi(t)$, a current $I_R(t)$ is generated, that can be calculated as

$$I_R(t) = \frac{\phi(t) \cdot S \cdot Q \cdot M}{w \cdot e} = C \cdot S \cdot \phi(t) \tag{2}$$

The output of the front end electronics, as shown later in the paper, is

$$V_{LogOut}(t) = V_0 Log_{10} \frac{I_{IN}(t)}{I_{R1}} \tag{3}$$

where I_{R1} is a constant current (in this case 100 pA) generated inside the LogAmp chip. A zero point current I_{min} is externally added in order to avoid negative saturation in case $I_R \ll I_{R1}$. So $I_{IN}(t) = I_R(t) + I_{min}$.

The number of reactions R inside the tube and the fluence Φ measured by the detector between t_1 and t_2 are given by

$$R = \frac{1}{C}\int_{t_1}^{t_2} I_R(t)dt = \frac{1}{C}\int_{t_1}^{t_2} (I_{R1} \cdot 10^{V(t)/V_0} - I_{\min})dt, \text{ or, in discrete notation} \tag{4.1}$$

$$R = \frac{1}{C}\sum_i (I_{R1} \cdot 10^{V(t)/V_0} - I_{\min}) \cdot \Delta t_i, \text{ where } 1/\Delta t_i \text{ is the sampling rate} \tag{4.2}$$

And

$$\Phi = R/S \tag{4.3}$$

3. Front end electronics

The inner electrode of the BF_3 detector is connected to the high voltage supply and the outer one to the input of a fast logarithmic amplifier (AD8304 of Analog Devices) that collects and processes the current generated by the neutrons. The LogAmp uses dual supplies so that its input pin is at almost 0 V. With this arrangement, the outer wall of the detector is at ground potential (neglecting the input offset) and all the front end electronics is referred to ground; no high voltage isolation is required and only an outer shield is necessary to avoid noise pick up.

A fixed 100 pA current (I_{min}) is added to the detector current to avoid saturation with no neutron flux. The working principle of the logarithmic amplifier can be understood from the simplified SPICE model of Fig. 2.

If the transistors are equal and isothermal, from Kirchoff's laws and Ebers–Moll equations [14] the following system results:

$$V_2 = V_T \ln\left(\frac{I_{IN}}{I_S}\right) \quad V_3 = V_T \ln\left(\frac{I_{R1}}{I_S}\right) \quad V_4 = V_T \ln\left(\frac{I_{R2}}{I_S}\right) \tag{5.15.25.3}$$

where

$$V_T = \frac{kT}{q} \tag{6}$$

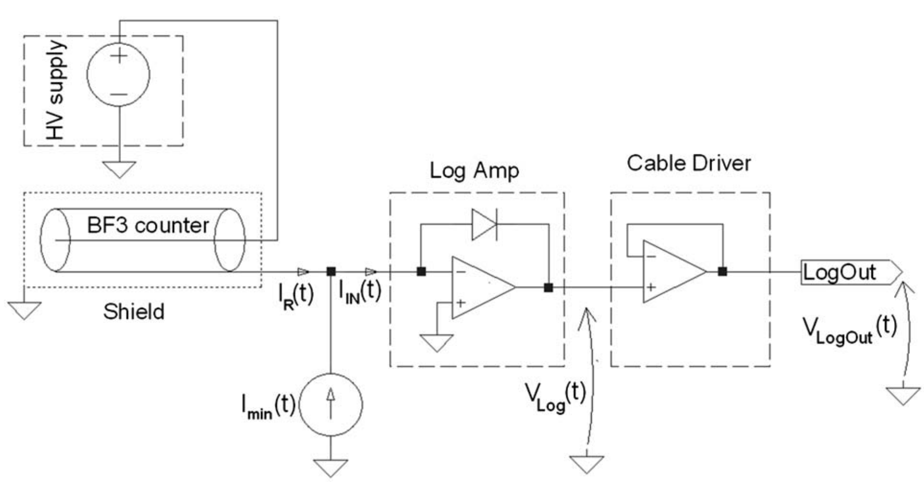

Fig. 1. General scheme of the detector.