PANDORA - a new device for radiation protection at DESY *

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Abstract

A new device for radiation protection studies was developed by DESY and BERTHOLD GmbH. This detector combines a conventional ^3He proportional counter and a scintillator-photomultiplier system for radiation measurements. In this report simulations of realistic radiative background conditions at an accelerator as well as the response of the detector are described.

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1 Introduction

In the environment of accelerators very special conditions exist. The radiation protection monitoring has to deal with high energy radiation as well as pulsed radiation. It is very problematic to detect accurately this radiation. First you need more then one conventional detector for γ and neutron radiation. On the other hand it is not trivial to calibrate your detector at high energies because there are no adequate calibration fields available. Also the efficiency at high energies is rather low. In order to solve this problems DESY in collaboration with the BERTHOLD GmbH designed a new detector, called PANDORA. This powerful detection system allows simultaneously the measurement of both the neutron and the γ radiation. Furthermore, the detector is sensible to pulsed neutron radiation fields. In this report the simulation of the device PANDORA by means of the program package FLUKA is outlined. In the following I would like to give a brief overview about the theoretical basics as well as a summary of the results.

2 What is FLUKA?

For the simulation of PANDORA a Monte Carlo tool, called FLUKA, was utilized. FLUKA [5, 6] is used for the calculation of particle transports as well as the interactions of those particles with matter. It uses the language FORTRAN 77 and is distributed by CERN. One can apply FLUKA for the evaluation of shielding, you need i.e. next to accelerators, for dosimetry and for example also to design a detector, like discussed in this report. This Monte-Carlo simulation tool provides the needed data for the propagation or interaction of about 60 particles.
A very helpful additional tool for the application of FLUKA is the graphical interface FLAIR [1], provided by CERN.

2.1 Neutrons

Because we examine the behavior of a neutron detector we have to take into account some quirks of FLUKA with respect to the neutrons. First there are two categories of neutrons, high energy and low energy neutrons, separated by an energy border of $E_b = 19,6$ MeV. For high energy neutrons default settings exist as well as an energy binning of personal choice. However, for low energy neutrons FLUKA uses a special cross section library divided into 72 energy groups, where the differences of two energies are nearly constant in a logarithmic scale. There are also more then 140 materials, sometimes at different temperatures, included. To solve this confusion of different energy deposition libraries a so called kerma factor is introduced (with the exception of hydrogen). The kerma factor K describes the total kinetic energy of all charged particles exempt by uncharged particles per unit mass of the target:

$$K = \frac{dE_{kin}}{dm} \tag{1}$$

The calculation is done by a 5^{th} order Legendre polynomial.

2.2 Scoring with the FLUKA option usrtrack

In FLUKA there are different possibilities to score the particle transport. For example you can score a specific nuclides with *resnucl*. In the simulation we used the so called *usrtrack* card for scoring. The *usrtrack* card estimates a track length fluence (track length is the length of the tracks of neutrons in a volume) resulting in the differential distribution of fluence per energy (given in counts per cm^2 per GeV per primary particle). For more informations see section 4.2.

2.3 Geometry

One of the most important and also most sensitive part of FLUKA is the construction of the geometrical parts of the objects under consideration. In order to facilitate the creation of e.g. sophisticated detectors pre-build modules are provided in the Combinatorial Geometry (CG) package. A choice between a few simple bodies, like infinite cylinders, planes, truncates and so on, which one can combine to a tall detector, is possible. But the user has to be careful with the definition of the bodies and regions, i.e. it is forbidden to have more then one defined region in the same area.

3 The detector

The neutron detector PANDORA consists of two different parts. The first one is a helium proportional tube and the second one is a scintillator combined with a photomultiplier, as described in section 4.1. Hence PANDORA includes a neutron detector as well as a γ detector. Additionally the detector is very small and light. Thus it's perfect for daily practice. But there is another very convincing feature of this detector: he is sensitive to pulsed neutron beams, also. For this purpose the special nuclear reaction (^{12}C(n,p)^{12}B) inside the scintillator is examined.
Figure 1 and 2 displays the real detector as well as the simulation geometry realized with the program package SimpleGeo [3]. This tool allows in an easy way to display the FLUKA geometry. There is another function where one can fade out some part of the geometry, which is very nice to check the correctness of the work. The different colors show the different materials used for building the detector.

The lower box in Figure 2 includes the main electronic part of PANDORA. The cylindrical part contains the ^{3}He proportional tube and is made of the moderator material. In this case polyethylene was used. Inside there are two cadmium plates around the

Figure 1: Real geometry of the neutron detector PANDORA

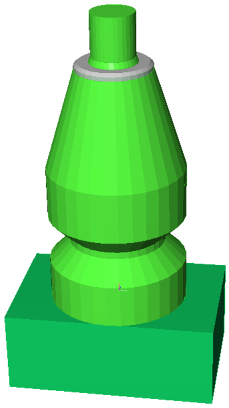

Figure 2: FLUKA geometry of the neutron detector PANDORA

tube with an influence on the shape of the energy dependent response. The top of the detector includes both the scintillator and the photomultiplier for γ radiation detection as well as in order to detect high energy neutrons respectively pulsed neutron beams. For more information see ref. [7].

4 Physical basics

4.1 Neutrons

In radiation safety especially at accelerators neutron protection is of highest importance. In order to satisfy the requirements on the newly developed detector one has to consider some physical basics.
The sources of neutron radiation are always nuclear reactions, either fission or fusion. Especially nuclear transformation of light elements cause a high yield of neutrons. Neutrons with energies over $E \approx 20\ MeV$ interact mostly via spallation. A spallation is an inelastic nuclear reaction where the neutron hits a nucleus and this emits a lot of secondary hadrons like other neutrons or protons. At lower energies different kinds of interaction exists. First the elastic scattering, where the neutron transmits energy according to:

$$\Delta E = \frac{4M}{(M+1)^2} \cdot \left(E_n \cdot \cos^2\theta\right) \tag{2}$$

where M is the mass of the target, E_n the energy of the neutron and θ the scattering angle. This kind of interaction is very import in soft tissue, where the scattering takes place at the hydrogen, due to the high cross section and the associated high energy transfer.

The second interaction mechanism is the inelastic scattering. Here the neutron hits the nucleus producing observable gamma radiation when the nucleus drops from the excited to the ground state.
Finally there is the neutron capture (also called (n,γ) reaction) with an excitation of the nucleus due to the capture of a neutron. Similar to the inelastic scattering this causes gamma radiation as a result of the transition between excited and ground state.

The importance of neutron reactions for radioactive protection with respect to other radiation like electron radiation or x-rays comes from the physical origin of different interactions. First they doesn't interact with the atomic shell, but with the nucleus, because they have a neutral electrical charge. So they can only interact via weak or strong interactions. The other difference is, that even a γ radiation field attend the neutron radiation. In this context there is the important quantity called relative biological effectiveness Q (RBE). It takes into account the energy dose in tissue. So it's a quantity for the harmfulness of the radiation for human being. The result of the product of energy dose and this factor is the so called dose equivalent A (unit Sievert $[Sv]$):

$$A = Q \cdot \frac{dE}{dm} \tag{3}$$

This report only discusses the ^{3}He proportional counter, because it is used at PANDORA, but there exists a lot of more devices for neutron radiation detection. Thermal neutron can be detected by the detector. The reaction that take place is the following:

$$n +_2^3 He \rightarrow_1^3 H + p \tag{4}$$

Afterwards the emitted proton can be detect in the proportional counter volume due to the electrical charge. The detection can be disturbed particular by the hull of the detector, in particular for high energy neutrons.
As aforementioned there is also always γ radiation beside the radiation field of the neutrons. Therefore a detector is needed as well for γ radiation i.e. scintillators in combination with photomultiplier or gas detectors.

4.2 Convolution

To calculate the number of ^{3}He(n,p) reactions in the helium proportional counter first one needs the definition of the track length T (cf. 2.2):

$$T = \int\limits_E \frac{dT(E)}{dE} \cdot dE \quad \text{with} \quad \frac{dT(E)}{dE} = \int\limits_V \frac{d\Phi(E,\vec{r})}{dE} dV \tag{5}$$

where Φ is the fluence (number of neutrons per area). The track length convoluted with the total cross section $\sigma(E)$ considering the particle density of the helium gas you get the desired number of ^{3}He(n,p) reactions:

$$N = \int\limits_E \int\limits_V \frac{d\Phi(E,\vec{r})}{dE} \cdot \sigma(E) \cdot n(\vec{r}) dV dE \tag{6}$$

Considering the density as constant ($n(\vec{r}) = n = const$) and introducing the macroscopic cross section $\Sigma(E) = \sigma(E) \cdot n$ we get the following ultimate solution:

$$N = \int\limits_E \frac{dT}{dE} \cdot \Sigma(E) dE \tag{7}$$

The term $\frac{dT(E)}{dE}$ is provided by FLUKA where $\Sigma(E)$ is listed in databases like [4]. In everyday life the interested value is the response R of the detector. The response is defined as the counts of ^{3}He(n,p) reactions per neutron per beam area
(unit: $[R] = \text{cm}^2!$). Therefore one has to multiply the number of ^{3}He(n,p) reactions by the area A of the considered volume. With eq. 7 the response for one primary energy can be calculate:

$$R = A \int\limits_E \frac{dT(E)}{dE} \cdot \Sigma(E) dE \tag{8}$$

but in the present case we look for a set of energies E_p. Finally, we get the final solution:

$$R(E_p) = A \int\limits_E \frac{dT(E_p, E)}{dE} \cdot \Sigma(E) dE \tag{9}$$

5 Results of the simulation

The aim of this chapter is to present the results of the simulation as well as some details of the analysis. In radiation protection physics we are mostly interested in the equivalent dose A, introduced in section 4.1. As explained in 2.2, we get from FLUKA the neutron fluence, therefore we have to convert the fluence given in counts per neutron$/cm^2$ into dose given in counts per pSv. The conversion function shown in Figure 3 was calculated by Pelliccioni up to 10 TeV [8].

From Fig. 3 one can see that for higher neutron energies there is an increasing dose. Furthermore one needs the cross sections of the used nuclear reactions: ^{3}He(n,p)^{3}H for the helium proportional tube and ^{12}C(n,p)^{12}B in the scintillator. These is displayed in Figure 4.

For thermal neutrons the cross section is very high (over 10^3 $barn$). Due to this the ^{3}He proportional tube is working well for low neutron energies, as already explained in section 3. The cut-off at energies about 10^{-2} GeV is not physical, but artificial. For energies up to 10 MeV the cross section for the ^{12}B(n,p) reaction is increasing. In this energy region a scintillator counter is used.

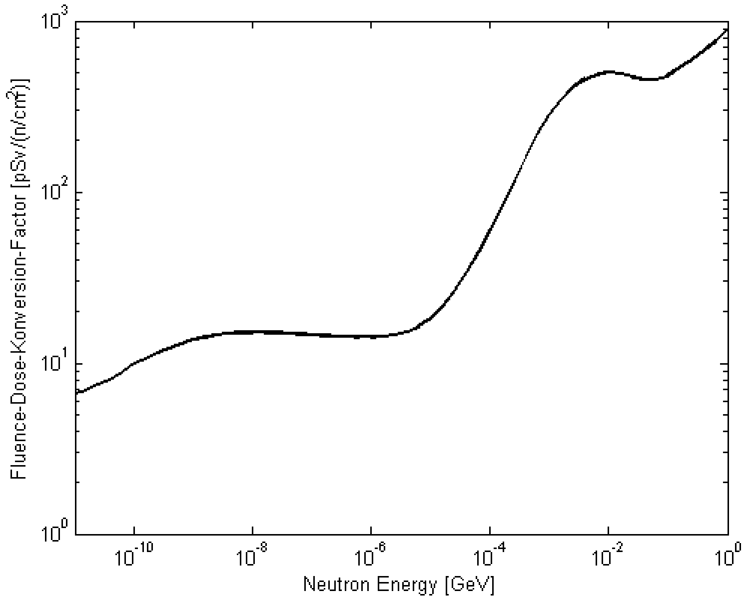

Figure 3: Fluence-dose-conversion function

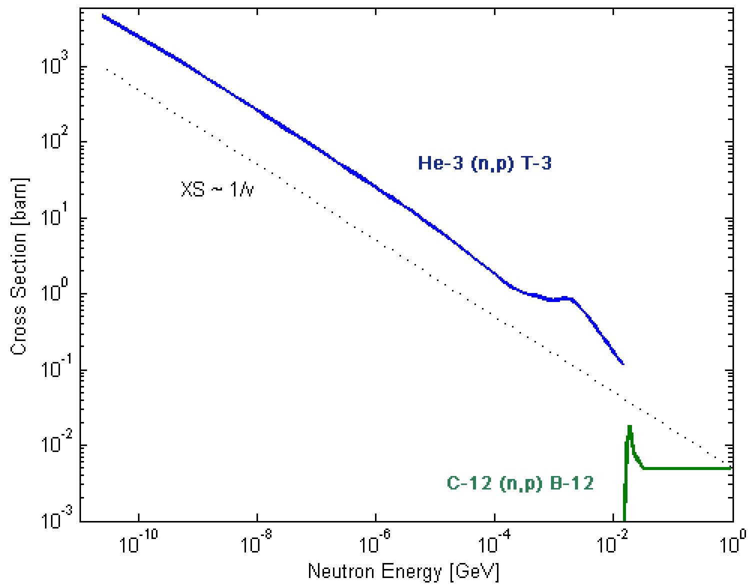

Figure 4: Cross sections of the used nuclear reactions

To probe the response of PANDORA one has to look first at the response of the helium proportional tube. Figure 5 displays the results of the simulation.

The upper curves represent the response in counts per neutron/cm^2. The light blue

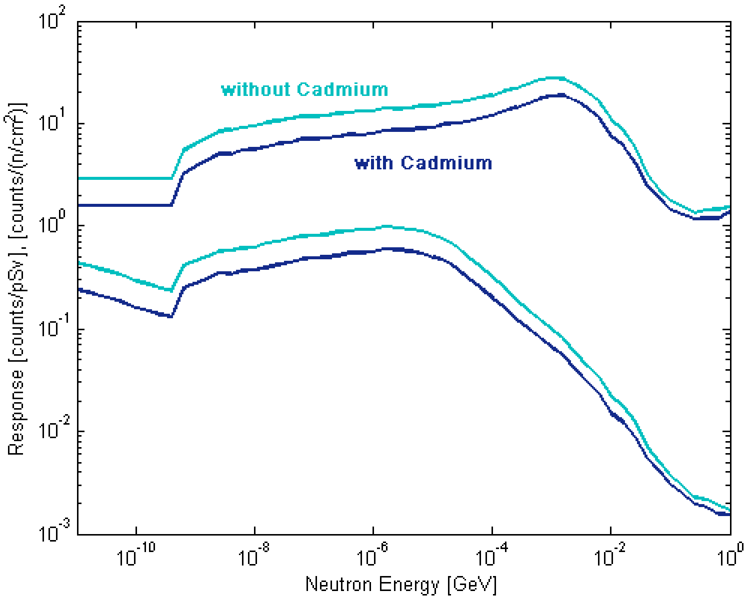

Figure 5: Results of the simulation for the response of the helium proportional tube

one depicts the response for the detector without the cadmium plates and the dark blue one with the cadmium plates. This is the direct result of the FLUKA simulation. The lower curves represent the response in counts per pSv. So this is the result of the simulation data divided by the fluence-dose-conversion function. There is a much more higher response for low energies (thermal neutron energies up to roughly 10 keV) as we discussed in the theoretical part (see also section 3). On the other hand this reveals that for high energy neutrons the detector is actually senseless. The graph also displays, that the effect of the cadmium plates is small. Only at high energies there is a little difference between the two curves. To analyse the response of the scintillator we first check on the response of the ^{12}B reaction. The response in counts per neutrons/cm^2 is demonstrate in Figure 6.

For neutrons with energies lower than approximately 10 MeV this kind of detection is actual senseless. But for higher energies there is a response of the scintillator. If one compares this response with that one of the helium proportional tube one has to keep in mind that different scales are presented, so the response of the helium detector for low energy neutrons is roughly about two orders of magnitude higher then the response of the scintillator for high energy neutrons.
FLUKA provides the energy deposition in a special region, too. Figure 7 view the energy deposition in the scintillator.

The upper black points show the electromagnetic energy deposition in pGy per neutron/cm^2 only. Whereas the upper red curve represents the complete energy deposition, electromagnetic and also hadronic, due to recoil protons. The lower points as well

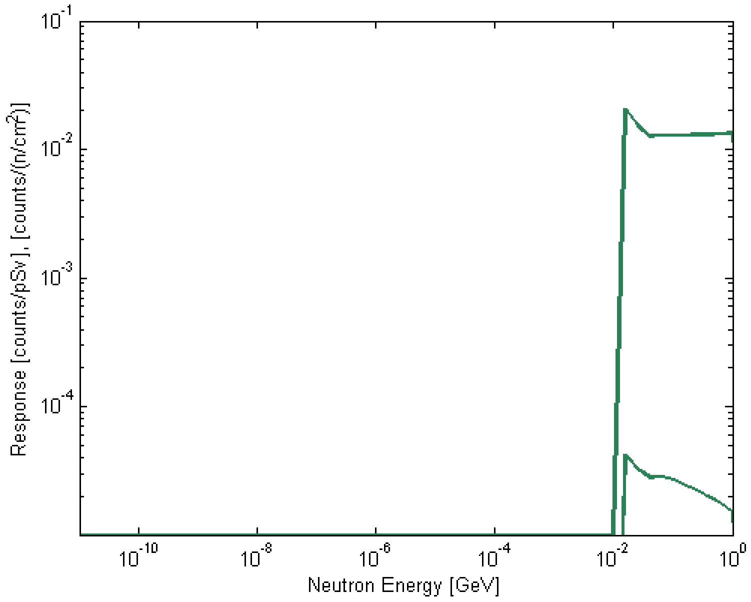

Figure 6: Results of the simulation for the response of the ^{12}B reaction

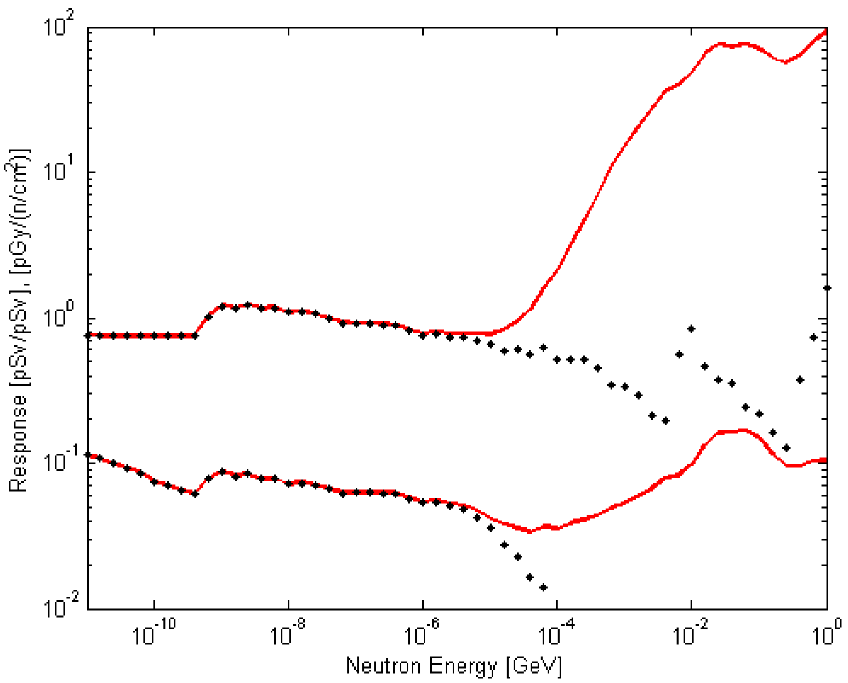

Figure 7: Results of the simulation for energy deposition in the scintillator

as the lower red curve typify the energy dose per equivalent dose in pGy per pSv.

At least Fig.8 displays two real neutron spectrums. The red curve shows the neutron spectrum calculated by FLUKA after a proton beam with an energy of $E_p = 350\ GeV$ was hitting a copper target. The spectra was simulated at a point 560 cm lateral at an angle of 90°, whereas the last 60 cm was made of standard concrete. The blue one pictures the neutron spectrum of an Americium-Beryllium source.

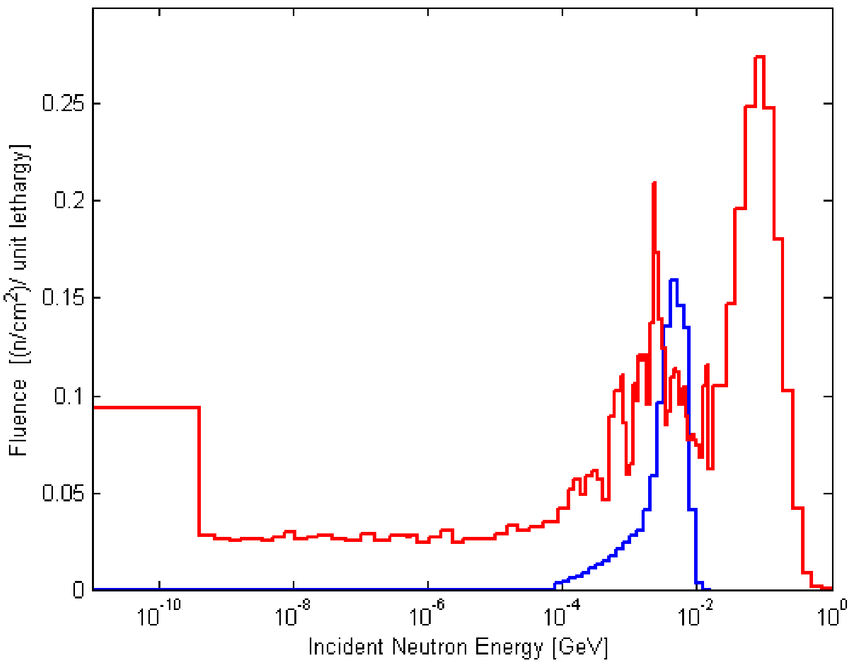

Figure 8: Real neutron spectra

For the Americium-Beryllium source a measurement of the ^{3}He proportional tube response was performed. The response for the ^{3}He(n,p)^3T reaction was measured to 4 counts per neutron/cm^2. The simulation gives a value of 14 counts per neutron/cm^2. The reason of this different values is actually not understand yet. A possibility is that the Am-Be source is burnt out as a consequence of the short α particle range. Another reason could be the efficiency of the ^{3}He proportional tube.
For the neutron spectrum at a proton accelerator ($E_p = 7,5\ GeV$) a measurement for the scintillator response was performed, too. The neutron spectrum at the measurement point (shielding: 2.5 m of total thickness) should be the same like the red curve in Figure 8 (cf. [7]). The response of the ^{12}C(n,p)^{12}B reaction was measured to 0.0032 counts per neutron/cm^2. This corresponds to a dose of 6.7 $\cdot 10^6$ counts per pSv. The simulation provides 0.014 counts per neutron/cm^2 or respectively dose of 30 $\cdot 10^6$ counts per pSv.

The reason for this difference is given by the competitively reaction $^{13}C(g,p)^{12}B$. In the measurement the hull of the detector was made of graphite and not of polyethylene. So this could also a possible explanation.

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