Experimental study for improving the angle dependence of the response of PADC-based personal neutron dosemeters

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HIGHLIGHTS

- The response of a two-orthogonal-element PADC personal neutron dosemeter have been studied.
- The angle response is greatly improved with respect to a single element planar configuration.
- The new configuration is suitable for ready implementation in dosimetry services.

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ABSTRACT

The large angle dependence of the \( H_p(10) \) response in PADC-based personal neutron dosemeters constitutes a serious concern in operational radiation protection dosimetry. For planar dosemeters, the typical \( H_p(10) \) response falls by half or more when the incidence angle changes from 0° to 60°. To reduce this source of systematic uncertainty, configurations based on multiple detectors at different angles have been developed, but their complex geometries constitute an important obstacle to the implementation in routine services.

This works proposes a simplified configuration, based on two orthogonal PADC detectors, which is suitable for the implementation in the routine service of INFN-LNF (Frascati).

This system was tested, using a ISO slab standard phantom, in the following reference neutron fields: \(^{241}\)Am–Be and 252Cf(D2O) available at ENEA-Bologna, and 1.2 MeV, 5 MeV and 14.8 MeV mono-chromatic beams available at PTB Braunschweig. Incidence angles of 0°, ±15°, ±30°, ±45° and ±60° were chosen. The sum of the track density in the PADC parallel to the phantom and that in the detector normal to the phantom face, was regarded as "dosemeter reading". On this basis the \( H_p(10) \) response was calculated for different energies and incidence angles. As expected, the angular response of the two-orthogonal-element dosemeter is highly improved with respect to that of a single planar PADC.

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1. Introduction

At INFN—LNF (Frascati, Rome) a chemically etched PADC based fast neutron dosimetry service has been established for the needs of the radiological surveillance around the DAΦNE high energy e⁺/e⁻ collider (Bedogni et al., 2008). Whilst the area dosimetry system relies on a four-element planar configuration (Bedogni et al., 2008a), an individual monitoring system for neutrons is not implemented yet. The large energy and angular dependence of the response in terms of \( H_p(10) \) are the main concerns in PADC based personal dosimetry. Because the energy distribution of the workplace neutron fields in DAΦNE is known, workplace-specific factors to correct for the energy dependence of the PADC dosemeters have been derived (Esposito et al., 2008). Consequently, the remaining problem to investigate is the angle dependence of the \( H_p(10) \) response.

Most of the PADC-based personal neutron dosemeters rely on planar configurations. Because of the planar geometry, an increase in the angle between the incident neutrons and the normal to the detector surface (termed "incidence angle") results in an increase in the fraction of secondary particles having incidence angles higher than the critical angle, thus decreasing the number of readable tracks. As a result, the \( H_p(10) \) response falls by half or more when the incidence angle changes from 0° to 60° (Morelli et al., 2006; Tanner et al., 2005). To reduce this source of systematic uncertainty, configurations based on multiple detectors at different angles have been developed. An example is the pyramid-shaped dosemeter (Harvey, 1992; Devine et al., 1996; Gopalani et al., 2003).

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This work proposes a simplified configuration, based on two orthogonal PADC detectors (also termed “double dosemeter”), which is suitable for a ready implementation in the routine service of INFN-LNF. The response of this dosemeter was determined as a function of the energy (from 1.2 to 14.8 MeV) and of the incidence angle. As a term of comparison, the energy and angle responses of a single-element planar dosemeter (termed “single dosemeter”) were also determined. The dosemeters were compared using numerical indexes that quantify the variability of the response as a function of the energy and/or the incidence angle.

2. Materials and methods

The PADC (with 0.1% dioctyl-phthalate) is produced by the Italian company Intercast Europe S.p.A. A single detector has dimension 2.5 cm × 3.5 cm × 0.14 cm. Because the detector acts also as n-p converter, only one side is counted. In the single dosemeter configuration this side is facing the phantom. The double dosemeter (see Fig. 1) is composed by a detector parallel to the phantom face, plus another that is normal to the phantom face. The normal dosemeter may be exposed, especially for high-energy neutrons, in non-equilibrium condition. However, if a symmetrical distribution of incidence angles is supposed as in this work, this effect does not significantly affect the results.

The PADC detectors are stored at low temperature (−30 °C), to limit the ageing effects. After irradiation, the detectors are processed through a pre-etching of 1 h in a 60% ethanol followed by a 10 h etching in 6.25N KOH solution at 70 °C, followed by a 10 h etching in 6.25N KOH solution at 70 °C (Morelli et al., 1999). The read out is performed at the INFN-LNF with an automated reader (Bedogni et al., 2008) equipped with an epi-illuminated microscope and an 8 Mpixel USB camera (3272 × 2469 pixels, 256 grey levels). For each detector, four fields of view are analysed for a total scanned area of 2.224 cm². The final resolution is 2.5 μm/pixel. A Labview program controls the motion, acquisition and counting processes.

Irradiations of the double dosemeter in terms of $H_{p(10)}$ have been performed using a ISO slab phantom and incidence angles of 0°, ±15°, ±30°, ±45° and ±60°. The following reference fields have been used:

- $^{241}$Am–Be and $^{252}$Cf(D$_2$O) available at ENEA-Bologna.
- 1.2 MeV, 5 MeV and 14.8 MeV mono-chromatic beams available at PTB Braunschweig.

To compare the results obtained with mono-chromatic or continuous calibration spectra, the calibration fields have been identified through their value of dose equivalent average energy, $E_{th}$, as defined and tabulated in ISO Standard 8529-1 (ISO, 2001). Whilst for mono-chromatic spectra this energy coincides with the nominal beam energy, for $^{241}$Am–Be and $^{252}$Cf(D$_2$O) its value is 4.4 MeV and 2.1 MeV, respectively.

For every energy and incidence angle, nine double-dosemeters were exposed. The dosemeter reading is defined as the sum of the track density of the PADC parallel to the phantom face ($N_{par}$) and that of the detector normal to the phantom face ($N_{norm}$). This value normalized to the delivered $H_{p(10),a}$ value provides the dosemeter response, as shown in Eq. (1):

$$R(E_{th}, \alpha) = \frac{(N_{par} + N_{sum})}{H_{p(10),a}}$$  \hspace{1cm} (1)

In addition to the double dosemeters, lots of nine single-element planar dosemeters have been exposed in the same conditions. This allowed appreciating the improvement, in terms of

### Table 1

$H_{p(10)}$ responses of the double and the single dosemeters, as a function of the incidence angle and of the neutron energy. The data are normalized to the Am–Be source (4.4 MeV) and normal incidence ($\alpha = 0°$). The variability index $\nu_a$ is reported for each energy and dosemeter type.

<table>
<thead>
<tr>
<th>$E_{th}$ (MeV)</th>
<th>Energy- and angle- dependent $H_{p(10)}$ response normalized to Am–Be</th>
<th>Single dosemeter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Double dosemeter</td>
<td>1.2</td>
</tr>
<tr>
<td>Angle $\alpha$ (deg)</td>
<td></td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60°</td>
</tr>
<tr>
<td>$\nu_a$</td>
<td>±2%</td>
<td>±5%</td>
</tr>
</tbody>
</table>
The angle dependence of the neutron incidence energies are studied. The data are normalized to the normal incidence for each energy. Calculated with Eq. (2):

\[ R_{\text{central}}(E_H) = \frac{\max[R(E_H, \alpha)] - \min[R(E_H, \alpha)]}{2} \]

where the maximum and minimum of the response are obtained, at fixed energy \( E_H \), by varying the incidence angle \( \alpha \).

Table 2

<table>
<thead>
<tr>
<th>Index</th>
<th>Single dosemeter</th>
<th>Double dosemeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_{\text{max}} )</td>
<td>±54%</td>
<td>±8%</td>
</tr>
<tr>
<td>( v_{\text{av}} )</td>
<td>±40%</td>
<td>±22%</td>
</tr>
<tr>
<td>( v_{\text{av},00} )</td>
<td>±60%</td>
<td>±29%</td>
</tr>
</tbody>
</table>

\( R_{\text{central}} \) is the central value of the response, i.e. the half sum of the maximum and the minimum response.

Figs. 2 and 3 compare the angle dependence of the response for the double dosemeter with that of the single-element planar dosemeter for the \(^{241}\text{Am–Be} \) and \(^{252}\text{Cf(D}_2\text{O)} \) sources. The data are normalized to the 0° response for every energy. Uncertainty bars (one sigma) are always higher than ±10%. The improvement in the angle response, from the single dosemeter to the double dosemeter, is evident from both Figures.

Table 1 and Figs. 2 and 3, \( v_{\text{av}}(^{241}\text{Am–Be, } E_H = 4.4 \text{ MeV}) \) changes from ±39% to ±8% when passing from the single dosemeter to the double dosemeter. In analogy, \( v_{\text{av}}(^{252}\text{Cf(D}_2\text{O), } E_H = 2.1 \text{ MeV}) \) passes from ±19% to ±5%.

The angle dependence of the response is considered for all studied energy in Fig. 4. For a given energy the data are normalized to the normal incidence response at that energy. The maximum value of \( v_{\text{av}}(E_H) \), termed \( v_{\text{av},00} \) is ±8% for the double dosemeter. This corresponds to \( E_H = 4.4 \text{ MeV} \) \((^{241}\text{Am–Be})\). For the single dosemeter this is ±54% and corresponds to \( E_H = 1.2 \text{ MeV} \). This data are shown in Tables 1 and 2.

The maximum relative variability of the response as a function of the neutron energy, in normal incidence condition \((\alpha = 0^\circ)\), is synthesized with \( v_{\text{av}} \) and is calculated as follows:

\[ v_{\text{av}} = \frac{\max[R(E_H, 0^\circ)] - \min[R(E_H, 0^\circ)]}{\max[R(E_H, 0^\circ)] + \min[R(E_H, 0^\circ)]} \]

The energy dependence of the response for the single and the double dosemeter is shown in Fig. 5. Here the data are reported for normal incidence \((\alpha = 0^\circ)\) and are normalized to the Am–Be. Also data for the bare \(^{252}\text{Cf source} \) were included. The single and the double dosemeters show comparable energy dependence, except for \( E_H = 14.8 \text{ MeV} \). The quantity \( v_{\text{av}} \) is ±40% for the single dosemeter and ±22% for the double dosemeter (see Table 2).
If the energy and angle dependence of the response are considered together, the maximum relative variability $v_{a,EH}$ can be defined:

$$v_{a,EH} = \frac{\max_{a,EH} |R(E_H, \alpha)| - \min_{a,EH} |R(E_H, \alpha)|}{\max_{a,EH} |R(E_H, \alpha)| + \min_{a,EH} |R(E_H, \alpha)|}$$ (4)

It should be noted that if a normal distribution is assumed to describe the occurrence of the $R(E_H, \alpha)$ in practical measurements, the relative standard uncertainty of $R(E_H, \alpha)$ can be estimated as $v_{EH} / \sqrt{3}$ (EC, 2009).

Fig. 6 shows the combined energy and angle dependence of the double dosimeter response. The data are normalized to the Am–Be in normal incidence condition ($\alpha = 0^\circ$). The index $v_{a,EH}$ is $\pm 29\%$ for the double dosimeter and $\pm 60\%$ for the single dosimeter (see Table 2).

The ISO performance requirements (ISO, 2005) can be used to further compare the double and the single dosimeters. This Standard treats the energy and angle dependence independently. For energy dependence it requires $v_{EH} < \pm 50\%$. This is fulfilled by both dosimeters.

For angle dependence, the Standard states “the arithmetic mean of the response of a dosimeter at angles of incidence of 0°, 15°, 45° and 60° from normal shall not differ by more than 40% from the corresponding response at normal incidence”. This difference is $35\%$ for the single dosimeter and $10\%$ only for the double dosimeter.

Both dosimeters fulfil the ISO criteria. Nevertheless, the double dosimeter practically eliminates the angle dependence of the response, substantially improving the accuracy of the response when the irradiation geometry in not known a priori.

4. Conclusions

The energy and angle responses of a personal neutron dosimeter based on two orthogonal PADC detectors have been determined and compared with those of a single element planar dosimeter. The irradiations have been performed with monochromatic beams from 1.2 to 14.8 MeV and with radionuclide sources.

When passing from the single dosimeter to the double dosimeter, the maximum angle variability of the response changes from $\pm 54\%$ to $\pm 8\%$. When energy and angle are considered together, the maximum response variability changes from $\pm 60\%$ to $\pm 29\%$.

The proposed configuration certainly implies additional costs in terms of number of detectors and development of new holders, but the increased accuracy of the dosimeter response is a major achievement for a dosimetry service.

Acknowledgements

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