Optimization of Neutron Monitoring Detector for LHD experiments

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1. INTRODUCTION

The Large Helical Device (LHD) project is aimed at exploring the feasibility of helical plasmas for use in fusion applications; in particular, the project aims to demonstrate the confinement of steady-state currentless plasmas within the fields generated by superconducting helical and poloidal coils [1]. It is intended that D-D reaction experiments will be performed for the next phase of the LHD [2]. During these experiments, both 2.45 MeV neutrons arising from D-D reactions and gamma rays will be generated. For reasons of safety, the radiation dose arising from these sources in the working area or at the site boundary need to be evaluated as accurately and precisely as possible. At the site of NIFS (National Institute for Fusion Science), the annual dose on the site boundary is limited to 0.05 mSv. Therefore, it is necessary to evaluate the dose precisely even for the very small doses anticipated. However, the evaluation of neutron dose is much more difficult than that of gamma rays, because the neutron dose conversion factor per unit fluence varies considerably with neutron energy [3]. If the evaluated dose is substantially overestimated, then the experimental plasma physics program would need to operate under an unreasonable constraint. Conversely, underestimation implies imperfect monitoring. A reasonable goal would, therefore, be to evaluate the dose so as to eliminate gross over- or under-estimation.

An area monitoring network system, RMSAFE (Radiation Monitoring System Applicable to Fusion Experiments), is installed on the site of NIFS [4]. Figure 1 shows the points of the outdoor monitoring station. In addition to the outdoor monitoring stations, radiation monitors are also arranged in the LHD building.

The X-ray and gamma ray photon sensors located at the site boundaries consist of ionization chambers filled with pressurized argon gas. For neutron monitoring, helium-3 proportional counters with 2.5-cm-thick polyethylene moderators were employed, thereby emphasizing detection sensitivity over dose response.

In this paper, we describe the improved design of neutron counter system for converting count to dose. The characteristics of these counters were evaluated by calculation.

Fig. 1 Points of monitoring observation.

2. MODERATOR DESIGN for He-3 COUNTER
2.1 Single counter

The helium-3 counter we use has a diameter of 2.5 cm and a length of 30.9 cm. The filled gas pressure was approximately 10 atm. The energy response varied with the thickness of the moderator. Four types of cylindrical moderator were assumed for the response calculation, one each with a thickness of 2.5, 5, 10 and 15 cm. The characteristic of energy response for the helium-3 counter was obtained by using the Monte Carlo simulation code MCNP-4b [5]. The applied cross section data was based on the ENDF-B/VI data set. The neutron sources were given in a 42 energy group structure, in order to match the form of the radiation field data [2]. The distance between the point source and the center of the counter was set to 1 m. The response of the counter was obtained from the reaction rate of $^3$He(n, p)T in the sensitive volume. Figure 2 shows the counter response with each moderator for the 42 groups of neutron energies. The result of calculations with a 2.5-cm thick moderator reveal that the efficiency is almost constant up to 0.5 MeV, but thereafter gradually declines with increasing neutron energy. In contrast, the response with the thick moderator becomes close to the dose conversion factor.

![Energy dependence of helium-3 counter with 4 series of polyethylene moderator.](image)

2.2 Paired counter

When a single counter is used for evaluating dose, the dose evaluation is only able to measure the specific shape of the spectrum. If parts of the spectrum lie outside the detector range, the detected dose could be underestimated. In order to overcome this, the optimization of a paired counter consisting of two counters with moderators of different thicknesses was examined. The aim was to fit the energy response of this paired counter to the ICRP dose conversion factor. One of the two counters, i.e., the counter with a 2.5-cm-thick moderator, is fixed, since it is installed on the existing system and has good counting efficiency. The other counter is adapted with a 10-cm thick moderator, because moderator of this thickness shows a better dose response than thinner moderators.

$K_D$ or $K_R$ in the following each equation represent the difference between the dose conversion factor quoted from the ICRP Publ. 74 and that derived from the response of the counters.

$$K_D = \prod_{i=1}^{42} [V_i - \beta (R_{2.5,i} + \gamma R_{10,i})]^2$$

$$K_R = \prod_{i=1}^{42} \left| 1 - \frac{\beta (R_{2.5,i} + \gamma R_{10,i})}{V_i} \right|$$

where $V_i$ is the dose conversion factor for the ith energy group, and $R_m$ is the reaction rate with type m monitor for the ith energy group.

When optimized $\beta$ and $\gamma$ are chosen in order to minimize $K_D$ or $K_R$, the dose response of the paired counter will approximate the ICRP dose conversion factor. The coefficients $\beta$ and $\gamma$ were determined to be...
0.029, 14 for $K_D$ and -0.0097, -52 for $K_R$, respectively.

2.3 Joint paired counter

For the paired counter, it is necessary that one counter is set more than 30 cm away from others, so as not to shield each other. In order to reduce the required space for installation of the counter, the joint paired counter which is joined two moderators was designed as shown in Fig. 3. Figure 4 shows the energy responses on front incidence, a incident angle of $\phi = 0$ represented by the products of the counts multiplied by the coefficients determined from the manner in the section 2.2.

Since it is supposed that the response differs with neutron incident angles to the counter, the response in several energy groups are calculated. Figure 5(a) and 5(b) show the variations of the response ratio with incident angles on the X-Y plane for the forward counter and the backward counter, respectively. The ratio represents the response to that of the front incidence. Figure 6(a) and 6(b) show the results on the X-Z plane. These data result that the difference of the response is small within ± 60 $\theta$, within ± 30 $\phi$. Therefore, the counter should be set its Z-axis on the horizontal plane for the outdoor monitoring, considering the detection efficiency of the sunshine component.

Fig. 3 Joint paired counter

Fig. 4 Energy dependence of the joint paired counter, front incidence.
3. NEUTRON DOSE EVALUATION

The neutron fluence data at the site was calculated using the two-dimensional Sn radiation transportation code DOT 3.5 [6] by means of the FUSION-40 nuclear data set [7]. The number of neutrons generated from a standard one-shot experiment was assumed to be $2.4 \times 10^{17}$ for 2.45 MeV with a DD reaction, and $2.4 \times 10^{15}$ for 14 MeV with a DT reaction [2]. The LHD experimental hall has 2-m-thick concrete walls and a 1.3-m-thick concrete ceiling. The neutron energy spectra at several monitoring points on the site are shown in Fig. 7. Each spectrum comprises the combined values of the direct component and the skyshine component. The shape of the neutron spectrum differs among points, and is caused by the distance from the LHD or the height from ground level.

We analyzed the accuracy of the neutron dose evaluation at monitoring points on the site boundary by using the radiation field data in the above and the counter response data in section 2. The expected dose on each point is derived according to the following equation,

$$D_p = \sum_{i=1}^{42} [F_{pi} \times V_i]$$

where $D_p$ is the expected dose at point $p$, $F_{pi}$ the fluence at point $p$ for the $i$th energy.

The detected dose on each counter is derived as

$$D_{mp} = \sum_{i=1}^{42} [F_{pi} \times \beta(R_{2.5,i} + \gamma R_{10,i})]$$

where $D_{mp}$ is the detected dose at point $p$ with type $m$ monitor.
Neutron energy distributions at several points in the site.

Using the coefficients for counters in the section 2.2, the detected dose was calculated at each monitoring point in the manner described above. Since the energy responses of the joint paired counter were obtained only on some energy groups at intervals, the value of other energy groups were calculated by interpolation. The calculation results for each of these two types of counter are shown in Table 1. According to the different shape of the neutron energy spectrum between monitoring points, the ratio of the detected dose with the paired counter to the expected dose varied from 1.48 to 3.68 using the coefficients with minimum $K_D$, from 0.54 to 0.73 using that with minimum $K_R$. For the joint paired counter, these value varied with the energy spectrum shape and incident angle to the counter. Compared with the deviation among points in Tables 1, the response using the coefficients derived from $K_R$ shows a smaller deviation than that from $K_D$. As a consequence, the ratio of the detected dose to the expected dose becomes within 1.5, if the calibration factor $\beta$ is appropriately selected. This system can thus be applied to monitoring at the site boundary.

In this way, it is expected that the joint paired counter with a 2.5-cm and a 10-cm thick moderator can be used for evaluating dose more reliably based on a comparison of the count data from the paired counter and each of the constituent counters.

### Table 1. Ratio of the detected dose by the paired counter to the expected dose.

<table>
<thead>
<tr>
<th>Name of point</th>
<th>$K_D$</th>
<th>$K_R$</th>
<th>$K_D$</th>
<th>$K_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>3.36</td>
<td>0.70</td>
<td>3.79</td>
<td>0.73</td>
</tr>
<tr>
<td>IB</td>
<td>3.68</td>
<td>0.73</td>
<td>4.14</td>
<td>0.73</td>
</tr>
<tr>
<td>IC</td>
<td>3.00</td>
<td>0.67</td>
<td>3.38</td>
<td>0.67</td>
</tr>
<tr>
<td>IE</td>
<td>1.87</td>
<td>0.57</td>
<td>2.13</td>
<td>0.57</td>
</tr>
<tr>
<td>WA</td>
<td>1.48</td>
<td>0.54</td>
<td>1.69</td>
<td>0.54</td>
</tr>
<tr>
<td>WB</td>
<td>1.63</td>
<td>0.55</td>
<td>1.85</td>
<td>0.55</td>
</tr>
<tr>
<td>WC</td>
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<td>0.55</td>
<td>1.73</td>
<td>0.55</td>
</tr>
<tr>
<td>WD</td>
<td>2.05</td>
<td>0.58</td>
<td>2.33</td>
<td>0.58</td>
</tr>
<tr>
<td>WE</td>
<td>1.53</td>
<td>0.55</td>
<td>1.74</td>
<td>0.55</td>
</tr>
<tr>
<td>WF</td>
<td>1.56</td>
<td>0.55</td>
<td>1.78</td>
<td>0.55</td>
</tr>
<tr>
<td>WM</td>
<td>1.51</td>
<td>0.54</td>
<td>1.72</td>
<td>0.54</td>
</tr>
</tbody>
</table>

max / min: 2.5 / 1.4; 3.0 / 1.5

4. CONCLUSION

The paired counter which consists of 2.5-cm and 10-cm thick polyethylene moderators was designed in order to evaluate neutron dose from count data, since the dose response of the helium-3 single counter can not keep up with the variation of energy spectrum. The energy response which is close to the dose conversion factor was obtained from the suitable coefficients multiplied by the output counts from the counters with 2.5-cm and
10-cm thick moderator. The joint paired counter was also designed for reduction of the required space. The responses of these counters at monitoring points on the site boundary were obtained by the calculated data of the counter response and radiation field around LHD. The results shows that the detected dose from these counters varies within a factor of 1.5 range of difference under different energy spectrum between monitoring points. Therefore, the paired counter can evaluate the dose more practically than a single counter.

REFERENCES