Measurement of high energy neutrons ($E > 50$ MeV) at electron accelerators of Indus accelerator complex using bismuth fission detectors

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This paper reports the measurement of high energy neutron component ($E > 50$ MeV) carried out at the Indus-1 (450 MeV) and Indus-2 (2.5 GeV) electron accelerators (RRCAT, Indore, India). The study is based on the registration of neutron induced fission fragments from bismuth radiators in the adjoint solid polymeric track detectors. These bismuth fission detector (BFD) stacks are exposed at the injection septums of booster synchrotron, Indus-1 and Indus-2 storage rings, where the possibility of dose due to beam loss is expected to be maximum. The detection efficiency of BFD is enhanced by enlarging the detector surface area and accordingly a large area spark counter is fabricated for automatic and rapid counting of the track densities. The dose equivalent rates are found to be about 0.11 mSv/h at the booster synchrotron and the Indus-1 storage ring, and about 0.62-0.65 mSv/h at the Indus-2 storage ring.

Keywords: Indus accelerator, Neutron dosimetry, Bismuth fission track detector, Neutron fission, Photofission

1 Introduction

Indus accelerator complex of RRCAT (Indore, India) consists of a 20 MeV Microtron, a 450/700 MeV Booster, and the 450 MeV (Indus-1) and 2.5 GeV (Indus-2) storage rings$^1$. Figure 1 shows the layout of booster, Indus-1 and Indus-2. The radiation environment present in these types of accelerators is primarily due to the bremsstrahlung photons generated by interaction of high energy electrons with structural materials of the accelerator. The typical bremsstrahlung photon spectra (calculated) from 450 MeV and 2.5 GeV electrons are reported elsewhere$^2,3$. The bremsstrahlung photons having sufficiently high energies ($E_{\gamma} > 5.0$ MeV), further interact with the beam line components like injection lines, collimators, slits, beam stoppers, beam dumps, etc. to produce neutrons of varying energies by means of different photonuclear interactions such as giant dipole resonance ($E_{\gamma} < 40$ MeV), quasi-deuteron ($50 < E_{\gamma} < 300$ MeV), photo-pion ($E_{\gamma} > 140$ MeV). The giant resonance neutrons are emitted almost isotropically with an average energy of about 2 MeV. High energy neutrons ($E_n > 10$ MeV) emitted from quasi-deuteron and photo-pion interactions are usually peaked in the forward direction$^4$.

However, the neutron spectrum is typically formed by low energy (evaporation spectrum) and high energy neutrons (knock-on spectrum). In high-energy accelerators where the photon energy and intensity are high compared to the neutrons, it is difficult to experimentally measure the direct photoneutron component. In such electron accelerators, neutrons and photons contribute to largest percentage of dose even beyond the shielding$^5$. Since the radiation field here is often pulsed in nature (ns to $\mu$s) with high peak dose rates during pulse, the measurements using active detectors are difficult. Moreover, commonly used rem meters, especially for high energy neutrons, are heavy, bulky, do not respond properly in pulsed neutron fields and tend to underestimate the actual dose$^2$. In such situations, the bismuth fission detectors (BFD), as explained in next section, are found to be suitable for the measurement of neutrons beyond 50 MeV.

In this work, BFD stacks are used to measure the photoneutrons above 50 MeV in the Indus accelerator facilities at RRCAT, Indore. Attempts are also made to determine the contribution from photofission components.

2 Bismuth Fission Detector (BFD) stack

Figure 2 shows a single bismuth fission detector set-up. The Bi films are usually made up of a few mg/cm$^2$ material deposited on a thick (~100 $\mu$m) polymeric or low Z metallic substrate to support the bismuth film. The advantage of using polymeric
material as substrate is that it avoids the production of heavier spallation residues. The neutron-induced fissions in the Bi film, having sufficient range, are registered in the adjoining solid polymeric track detector (SPTD). The threshold energy of the detector system is determined from the $(n,f)$ cross-section (Fig. 3). The attractive characteristics of this detector are:

- Insensitive to RF interference.
- Does not respond to low LET particles and neutrons below 50 MeV.
- Smooth variation of cross-section with energy.
- Integral mode and almost permanent registration of the signal.
- Mono-isotopic, non-radioactive, light weight and convenient to expose.

Normally, multi-BFD stacks are used to enhance the overall detector response. When two Bi films on both side of the detector are used, it not only doubles the efficiency, also rejects the front-back asymmetry of the detector.

However, the high energy photons can also induce fissions in $^{209}\text{Bi}$. So, the experimental results need to be corrected for photofission contribution, if any.

### 3 Photofission Correction

If the gamma field is highly intense in terms of energy and fluence, then the photofission component may become comparable to that of neutron fissions. In that case, the dose values need to be corrected for the photofission components. The neutron-induced fission cross-section [$\sigma(n,f)$] and photofission cross-section ($\sigma(\gamma,f)$) for $^{209}\text{Bi}$ are compared in Fig. 3. The values of the $(n,f)$ cross-section up to 200 MeV are taken from Carlson et al., and Shcherbakov et al., 2001. For energies between 200 MeV and 1 GeV, the cross-sections derived from $^{209}\text{Bi}(p,f)$ cross-sections by Tommasino et al., and the measurements by Tarrio et al., are adopted.

As can be seen in Fig. 3, the recent cross-section measurements as available in EXFOR database, are slightly higher than the earlier reported values. Nevertheless the energy threshold is found to be unchanged.

For photofission cross-section, the values measured up to 500 MeV by Jungerman and calculated up to 1 GeV by Poyser et al., are considered. As can be seen from these curves (Fig. 3), the measured $(\gamma,f)$ cross-section peaks at about 400 MeV photon energy and then falls down. At the peak, the $(\gamma,f)$ cross-section is about 10 times less than $\sigma(n,f)$. However, the calculated $\sigma(\gamma,f)$ values show a smooth variation with energy and is about 20 times less than $\sigma(n,f)$. The total photofission component can be calculated by folding the bremsstrahlung spectrum with photofission cross-section.
4 Experimental Details

4.1 Calibration and measurements

Large area ($10 \text{ cm} \times 10 \text{ cm}$) bismuth fission detectors (BFD) (as shown in Fig. 2) are prepared by sandwicing the polymeric track detectors between two Bi radiators with infinite thickness, i.e. a thickness greater than the range of fission fragments in Bi. Infinite thickness ensures maximum possible interactions in the radiator corresponding to the best possible efficiency, beyond which any further increase in the thickness does not improve the efficiency. Several such BFDs are combined to prepare various BFD stacks. For calibration, these stacks are exposed at high energy reference field (CERF) in CERN, Switzerland and to quasi monoenergetic neutrons at The Svedberg Laboratory (TSL), Sweden. The neutron spectra and other relevant parameters of CERF and TSL are reported elsewhere\textsuperscript{13,14}. The measurements at Indus accelerator complex are carried out by exposing these BFD stacks at injection septums of the booster, Indus-1 and Indus-2 storage rings, where the possibility of beam loss is expected to be maximum. Three separate experiments are conducted for different time periods, as mentioned in Table 1. The first two experiments are carried out for different durations to check the reproducibility. The third experiment is conducted to determine the signals from photofission components by introducing a Pb block of 3.8 cm (Fig. 4) between two sets of BFD stacks so as to attenuate the contribution from photon components for one set of BFD stack (BFD-2 as shown in Fig. 4). In this experiment, the detector stacks are exposed for a longer duration as compared to the previous experiments, so as to allow sufficient signals to reach BFD-2.

4.2 Track development and counting

After irradiation, the track detectors are removed from the BFD stacks, etched with 30% KOH in water at 40°C for 2.5 h. A special spark counter with large spark head ($25 \text{ cm}^2$) is designed and fabricated to count the tracks. The track detectors are cut into four pieces to fit on top of the spark head. The sparks through the detectors and aluminized mylars are counted at 500 V after a pre-count discharge of 900 V. Each sample is counted several times and the average spark density (sparks $\text{cm}^{-2}$) is determined.

The dose equivalent values are determined using the calibration factor (mSv $\text{cm}^2$ spark$^{-1}$) obtained from CERF, mainly because it is reasonable to assume that the neutron energy distributions at both facilities have the same shape.

5 Results and Discussion

The dose equivalent values and the total exposure times are listed in Table 1. As evident from the Table 1 (1\textsuperscript{st} experiment), the dose equivalent rates are found to be the same at booster and Indus-1 injection septums. This is primarily due to the gradual ramping of 20 MeV beam, which is injected initially to booster injection septum. In each turn the beam has to pass through the injection septum chamber with amplified energy. Therefore, the beam of 20 MeV up to 450 MeV is found to pass through the injection septum chamber. There is always loss of electrons in the injection septum leading to the generation of photo neutrons as discussed earlier. The dose rates at the injection septum of Indus-2 (2.5 GeV) are found to be about 6 times higher than Indus-1. An exposure time of about 5 h at Indus-2 is found to be sufficient to receive enough signals on the detector. However, to check the consistency, the experiments are repeated for different durations (2\textsuperscript{nd} experiment). Similar results are obtained in the second experiment also. Moreover, it is also interesting to note that, the dose rate values in each location are found to be almost constant even at different periods of exposure.

Table 1 — Dose equivalent rates due to high energy ($E>50 \text{ MeV}$) photo neutrons at the injection septums of booster, Indus-1 and Indus-2. The random errors associated in the dose values are only standard deviations from the average counts obtained from the repetition of the spark counting procedure

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Location</th>
<th>Exposure time (h)</th>
<th>Dose equivalent rate (mSv/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>73</td>
<td>0.11±0.02</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>35</td>
<td>0.11±0.02</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>5</td>
<td>0.65±0.09</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>25.5</td>
<td>0.10±0.01</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>18.5</td>
<td>0.62±0.08</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>180</td>
<td>0.11±0.02</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>164</td>
<td>0.64±0.09</td>
</tr>
</tbody>
</table>

Note: A= Booster injection septum, B= Indus-1 injection septum, C= Indus-2 injection septum.
even though it depends on several beam parameters.

In the third set of measurement for the photo fission correction, the detectors are exposed for a much longer period. Results obtained from both the detector stacks (BFD-1 and BFD-2 in Fig. 4) are found to be almost the same and comparable to those obtained from the previous two experiments. This indicates that either the signals from photo fission components are too small to be registered in the fission track detector or the attenuation of photons through 3.8 cm Pb block is not sufficient to produce any significant changes in the spark numbers. Work is in progress to verify the results and to determine the photo fission correction factors using different detection set-ups and methods as well as using thicker Pb blocks.

6 Conclusions

Bismuth radiators coupled with solid polymeric track detectors are successfully used to measure the dose equivalent due to photo neutrons ($E>50$ MeV) at Indus high energy electron accelerator facilities. The dose rate values are found to be consistent for all sets of experiments conducted for different time periods. The photo fission components are not found to produce any significant changes in the signals registered in BFDs kept after 3.8 cm Pb block, so the results reported here are not corrected for the same.

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References