Combined use of an activation detector and an imaging analyzer for measuring the distribution spatial fluence in an accelerator building

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1 INTRODUCTION

At accelerator facilities, the primary beam from an accelerator hits various accelerator components, such as a deflector, collimator, slit, beam duct, beam monitor or target during beam transportation. From their beam-loss points, secondary neutrons are also emitted by nuclear reactions, which cause activation of the surrounding materials, such as a magnet, frame, cable, electric circuit, tube of the cooling water, vacuum pump or accelerator building. Such neutron often causes radiation damage to electronics circuits. In accelerator and experimental rooms, the neutron dose has been continuously monitored with a BF-3 proportional counter or a He-3 proportional counter. The cumulative dose of neutrons has also been monitored with a film badge, a thermoluminescence detector and/or a track detector using CR-39 plastic. A measurement of the spatial distribution of secondary neutrons in such rooms is very important to estimate the degree of neutron activation of various parts, to allow effective shielding, as well as feedback to accelerator operation and beam control and to lower the residual radioactivity. Unfortunately, it is very difficult to obtain the spatial distribution of neutrons with the above monitoring methods.

On the other hand, neutrons have been monitored by the activation detector method, which is very useful to monitor the spatial distribution. In the case of the usual activation detector method, each detector should be measured with a Ge-detector and a multichannel analyzer. Therefore, this method requires time-consuming gamma-ray measurements and tedious radioactivity calculations.

Recently, an imaging plate has been developed as a new technique of radiography. The imaging plate has been used so far to measure the radioactivity distribution of a material surface in X-ray diffraction studies. Although an imaging plate used for neutron detection has also been developed, many plates should be set in the accelerator room to obtain a neutron-dose map.

Then, in order to develop a rapid and simple monitoring method for the spatial distribution of neutrons, we tried the combined use of an activation detector and an imaging analyzer. The most important key point of this technique is that many activation detectors, such as foils, are pasted on the sampling point of the map, and the map is directly stacked on the imaging plate to develop the radioactivity of all sampling points simultaneously.

2 PRINCIPLE

2.1 Induced activity in the activation detector

When the primary beam hits the materials of an accelerator component, secondary neutrons are generated from the beam-loss points by nuclear reactions. The number of radioisotopes \( n \) induced in the activation detector can be calculated by

\[
 n = \frac{f \sigma N}{\lambda} \left(1 - \exp\left(-\frac{\lambda t}{\sigma}\right)\right),
\]

where \( \phi \) is the neutron flux \( (n/cm^2/sec) \), \( \sigma \) is the activation cross-section \( (cm^2) \), \( N \) is the number of target nuclides in the activation detector, \( \lambda \) is the decay constant of the induced radioisotope, and \( t \) is the irradiation time.

The radioactivity \( (Bq) \) is the product of \( n \) and \( \lambda \). Thus, the neutron flux \( (\phi) \) can be estimated by the induced radioactivity in the activation detector.

Because \( \lambda \) is the characteristic value of a radioisotope and \( \sigma \) depends on the target nuclide and the nuclear reaction, suitable detectors such as In, Au, Co, Mn, Na for thermal neutrons and Al for fast neutrons should be selected.

In this work, Au and Al foils were selected to monitor of the thermal and fast neutrons, respectively.

2.2 Absolute measurement of radioactivity

The absolute radioactivity was measured with a Ge-detector. The obtained peak counts \( (C) \) of a certain \( \gamma \)-ray has the following relationship:
\[ C = n \alpha \epsilon \exp \left( -\lambda t_1 \right) \int_{t_2}^{t_3} \exp \left( -\lambda t \right) dt \]

where \( n \) is the induced radioactivity at the end of irradiation, \( \alpha \) is the branching ratio of the \( \gamma \)-ray per decay, \( \epsilon \) is the detection efficiency of the Ge-detector, \( t_1 \) is the time interval between the end of irradiation and the start of a measurement, \( t_2 \) is the start time of the measurement and \( t_3 \) is the end time of the measurement. The detection efficiency of each energy of \( \gamma \)-ray at a certain position of measurement was calibrated with a standard \( \gamma \)-ray source.

2.3 Measurement of radioactivity using imaging plates

After an activation detector is exposed on the imaging plate for a certain time, the photoluminescence from the imaging plate is measured using an imaging analyzer. The intensity of the photoluminescence at a certain area can be read in units of photo-stimulated luminescence (PSL). The PSL has a linear relationship with the radioactivity (Bq) and the exposure time (min), as shown in the section of concerning experimental results. If the conversion factor between the radioactivity and PSL at a certain exposure time is obtained experimentally in advance, the radioactivity can be directly obtained by reading the PSL.

3 EXPERIMENTAL

The neutron flux was measured at the SF-Cyclotron, Center for Nuclear Study, the University of Tokyo. Small tips of gold and aluminum foils (11mmφ) were used for the activation detector. The \( ^{197}\text{Au}(n,\gamma)^{198}\text{Au} \), \( ^{197}\text{Au}(n,2n)^{196}\text{Au} \) and \( ^{27}\text{Al}(n,\alpha)^{24}\text{Na} \) reactions were used as the monitor reaction. In the beginning, activation foils were set along the beam-transport tube to monitor the neutrons under different operation conditions, such as protons of 20 and 25 MeV, deuterons of 30 MeV and alphas of 50 MeV.

In order to obtain a two-dimensional map of the neutron flux, activation detectors were set on the floor and the wall of the accelerator room. The maximum number of monitoring points in the accelerator room was about 60. The vertical distribution of the neutron fluence was monitored by detectors hung from the ceiling to the floor at intervals of 50 cm.

After the end of operation, the activation detectors were collected and pasted on the plan and the elevation for the accelerator room to indicate the monitoring points of each detector. The imaging plate (BAS III, Fuji Photo Film Co.) and the plan (or the elevation) were stuck together to develop the activities of the detectors simultaneously. The imaging plate was measured with a bioimaging analyzer (BAS-1000, Fuji Photo Film Co.). The intensity of neutrons each point on the map was calculated, and a color image of the neutron intensity was obtained as a two-dimensional map by software called MacBAS, provided by FUJIX Co. The conversion factor between PSI and Bq for \( ^{198}\text{Au} \) was calibrated by gamma-ray spectrometry using a Ge-detector in advance. An automatic gamma-ray spectrometer, which is composed of a Ge-detector (Canberra), a multichannel analyzer (SEIKO EG&G) and a small robot (Mitsubishi) for sample changing, was used for an absolute \( \gamma \)-ray measurement. The counting times were 2000 to 10000 sec for each activation detector. The foils were contacted on a Ge-detector surface.

4 RESULT&DISCUSSION

4.1 Effectiveness of the activation detector

In order to confirm whether the activation detector method is usable or not, the activation detectors were set on a place along with the beam-transport tube from the cyclotron, as shown in Fig 1. In this experiment, the proton energy was 20 MeV and the average beam current was about 2 \( \mu \)A. Fig 2. shows the dose rate of seven positions measured with the ionization chamber. The maximum dose rate was about 1 mSv/hr near to positions No. 3 and 4, and the dose rates decreased with the distance from the cyclotron.

Positions No. 3 and 4 were the upper and lower part of the beam tube, respectively. Figure 3 shows the neutron fluxes calculated based on the radioactivities of \( ^{198}\text{Au} \) induced in gold foils. The flux calculation was performed based on the assumption that neutrons are all resonance neutrons of the \( ^{197}\text{Au}(n,\gamma)^{198}\text{Au} \) reaction, and capture cross section is 1550 barn. The activity of \( ^{198}\text{Au} \) from the \( ^{197}\text{Au}(n,2n)^{196}\text{Au} \) reaction was negligibly small, and could be observed at the position of the maximum neutron flux. The trend of the neutron flux was similar to that of the surface dose at the monitoring position. Therefore, it was found that
the activation detector vividly showed the beam-loss position under each operation condition.

4.2 Effectiveness of an imaging plate

Nine gold foils, having different radioactivities ranging from 15 to 200 Bq were set on the imaging plate to confirm the usefulness of an activity measurement with an imaging plate. The exposure times (min) were also changed from 2 to 60 min. The obtained results are shown in Fig 4. In this figure, the overall exposure time was usually set at 20 min. An experimental equation for $^{198}$Au, $PSL = 1.11 \times [\text{activity}, \text{Bq}] \times [\text{exposure times}, \text{min}]$, was obtained from Fig 4. In the case of a $\gamma$-ray spectrometry, a $\gamma$-ray peak-area calculation and a decay correction of each sample should be made. On the other hand, many foils are simultaneously measured with the imaging plate without any decay correction within a short measuring time. However, the experimental calibration factor should be obtained for each radioisotope.

In the case of mapping the neutron flux, activation detectors are put at the monitoring positions of the map after the end of activation. Then, the imaging plate is homogeneously irradiated with an X-ray beam, and the homogeneity of the detection sensitivity is monitored. Table 1 shows the result of six sampling points. The obtained values ($PSL/mm^2$) are in good agreement with each other, and their %RSD is 4.1%. Therefore, a correction of the sensitivity at each position is not necessary.

<table>
<thead>
<tr>
<th>No</th>
<th>PSL/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1326</td>
</tr>
<tr>
<td>2</td>
<td>1376</td>
</tr>
<tr>
<td>3</td>
<td>1252</td>
</tr>
<tr>
<td>4</td>
<td>1276</td>
</tr>
<tr>
<td>5</td>
<td>1237</td>
</tr>
<tr>
<td>6</td>
<td>1266</td>
</tr>
<tr>
<td>Average</td>
<td>1288±52</td>
</tr>
</tbody>
</table>

4.3 Spatial distribution of neutrons in the cyclotron room

Figure 5 shows the result of an experiment where the proton energy was 25 MeV and the average beam current was 2mA. The beam was transported to Cave 2A. Gold foils were set on the floor and the wall of the cyclotron room and pasted on the map. The obtained imaging-plate result and map were overlapped again on the computer display to grasp the spatial distribution at a glance. It was found that the neutrons were not homogeneously distributed in the cyclotron room. The colored spots show the measuring positions of the activation detector. This figure emphasizes the difference in the neutron flux. The color means the degree of radioactivity; for instance orange means about $10^3$ cm²/sec and blue means about $10^2$ cm²/sec. The positions of high neutron flux were mainly localized near to the cyclotron and the analyzing magnet for the beam course to
Cave 2A.

4.4 Spatial distributions of neutron in the cyclotron room

In a second experiment, the deuteron energy was 30 MeV and the beam course was selected to be Cave 1. About 60 samples were positioned at the cyclotron room and the experimental rooms. Figure 6 shows the results of gold foils placed on the floor and the wall of the cyclotron room. By overlapping with the result of an imaging plate and map, the spatial distribution can be visually understood. This figure clearly shows that the major neutron source, that is, the beam-loss point, was the deflector of the cyclotron. This figure also emphasizes the difference in the neutron flux, as shown in Table 2. The difference between the maximum flux to the minimum flux was about one order.

**Table 3.** Minimum and Maximum flux of neutrons observed in the case of 30MeV deuteron irradiation

<table>
<thead>
<tr>
<th>Au weight(mg)</th>
<th>Au atoms</th>
<th>PSL</th>
<th>Bq (IP analysis)</th>
<th>Bq (at beam stop)</th>
<th>Neutron flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min 21.8</td>
<td>6.66E+19</td>
<td>235.1</td>
<td>8.5E+0</td>
<td>1.1E+1</td>
<td>7.38E+2</td>
</tr>
<tr>
<td>Max 22.3</td>
<td>6.81E+19</td>
<td>3359.0</td>
<td>1.2E+2</td>
<td>1.6E+2</td>
<td>1.03E+4</td>
</tr>
</tbody>
</table>

4.5 Vertical distribution of neutrons in the cyclotron room

Then, the vertical distribution of neutrons was measured in the same manner. The five measuring positions were selected from the cyclotron to the switch magnet, as shown in Fig. 7. Six activation detectors were hung from the ceiling at intervals of 50 cm. The experimental condition was almost the same as that mentioned in the previous section. The observed result is shown in Fig 8. The neutron flux gradually decreased with the distance from the cyclotron gradually. At position No.3, the neutron flux near to the floor level was higher than that at other heights. Generally, the vertical distribution of each measuring position was almost the same. This result was contrary to our expectation, which was that the maximum neutron flux could be observed on the beam line, and that the flux would decrease with the distance from the beam line. Because there are no experimental data of the three-dimensional distribution of neutrons in the accelerator room, this data will be compared with a theoretical calculation of the neutron propagation.
CONCLUSION

It was found that the activation detector method is very effective to measure neutrons emitted by beam loss during beam transportation in an accelerator room. A neutron fluence of $10^3$ n/cm$^2$/sec was measured using an exposure time of 10 min within a few % of the relative standard deviation. The linearity of PSI vs. radioactivity and the PSI vs. exposure time were very good.

To reduce the counting time of the activation detector and to grasp the spatial distribution of neutron, the combined use of an activation detector and an imaging plate was developed. The activated foils were pasted on the sampling points of the map and the map was stacked with the imaging plate at a certain exposure time. After the image data could be obtained with a bioimaging analyzer, BAS-1000, the neutron distribution could be shown as a two- or three-dimensional display by overlapping the map and the image data of the activation detector. The radioactivity of 70 to 80 pieces of detector could be simultaneously measured and easily converted to Bq.

These image data are very useful to grasp the spatial distribution of neutrons at a glance. The neutron flux at the floor and wall near to the beam-extraction side of cyclotron was high. The fluence of the opposite side of the beam extraction was low, due to the shielding effect of the main maget. It was found that neutrons were mainly produced at the beam-extraction position of the cyclotron, such as the deflector. The neutron flux
decreased with the distance from the cyclotron along the beam direction. On the other hand, the gradation of the vertical direction was small.

These quantitative data are also useful to reduce the activation of machine components. These data will also be reflected to the beam transport, the machine operation and the design of the beam-transport system. The radioactivity induced in the concrete wall was measured and compared with the result calculated by the neutron flux and the operation condition of the cyclotron. If the area of high neutron fluence was covered with a boron sheet, activation of the floor and wall could be effectively reduced. This experiment will provide an opportunity to visually understand the secondary neutron problem of an accelerator facility.

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6 REFERENCES


