The stand for irradiation of electronic boards at the INR RAS linac: estimation of particle fluxes, activation, and dose rate

L.N. Latysheva, S.G. Lebedev, N.M. Sobolevsky, A.V. Feschenko
Institute for Nuclear Research RAS, 117312 Moscow
Electronic board:
size 15×15×0.7 cm; composition (wt.%): silicon 90%, epoxy 5%, copper 5%; density 2.39 g/cc.

The following questions should be clarified:
Electronic board:
1. Heating rate of the electronic board.
2. Activation and cooling of the board, dependence of dose rate on time.
3. Fluxes of nucleons albedo from the beam trap to electronic board.

The beam trap (figure below):
1. Fluxes of secondary neutrons into experimental hall from various surfaces of the trap.
2. Activation and cooling of various elements of the trap.

Neutron fluxes in surrounding space, behind shielding of the linac tunnel (ground, mound thickness ~ 6 m).
Gray – heavy concrete, 3.6 g/cc, 3×3×4.5m. Red – heavy concrete, 3.6 g/cc, 125×125×125см. Black – the beam target, graphite 2.26 g/cc, 20×20×25cm. Purple – iron sheet of 1cm thick. White – borated polyethylene, 3.5% of $^{nat}$B, bricks NEUTROSTOP of 8cm thick. Surfaces for scoring of neutron fluxes into experimental hall are numerated as 10-15.
Photo of the proton beam trap

Photo by S.A.Gavrilov
Neutron fluxes into experimental hall from the most stressed surfaces Nos. 10 and 12 of the beam trap

At current of 1 mkA:

- 2.2 \times 10^7 \text{n/cm}^2/\text{s} into the upper hemisphere.
- 5.5 \times 10^5 \text{n/cm}^2/\text{s} in the horizontal direction.

Thus, neutron fluxes into experimental hall are quite large: 5.5 \times 10^5 \text{n/cm}^2/\text{s} in the horizontal direction and 2.2 \times 10^7 \text{n/cm}^2/\text{s} into the upper hemisphere. An additional biological shielding is required.
Albedo of neutrons and protons from the beam trap onto the electronic board
(comparison of fluxes inside the electronic board with and without the beam trap)

The board is irradiated with neutrons scattered back from the beam trap. However, the energies of these neutrons do not exceed 0.01 MeV, and their flux is ~10% of the neutron flux formed in the board itself. The albedo protons are absent. **Thus, the albedo irradiation is negligible and don't distort the results of the proton beam irradiation.**
Calculation of activation and cooling of a target assembly based on Beteman equations using the DCHAIN-SP code

The DCHAIN-SP code calculates the activation and cooling of a target under irradiation with an accelerator beam, as a function of time, taking into account all possible radioactive chains.

**The input data** for the DCHAIN-SP code are the production rates of nuclei-products inside the irradiated assembly, calculated by some Monte Carlo transport code, in our case - by the SHIELD code.

**The output** of the DCHAIN-SP is:
- activity of all radionuclides,
- energy of radioactive emission (energy release),
- spectra of gamma quanta,
for each target zone, at the times, specified by the user.

The DCHAIN-SP code includes the necessary **nuclear data**:
- decay data library,
- electron capture decay rate data library.

H.Takada, K.Kosako. *Development of the DCHAIN-SP for Analysis Decay and Build-up Characteristics of Spallation Products.*
Japan Atomic Energy Research Institute, JAERI-Data/Code 99-008.

N.M.Sobolevsky, L.N.Latysheva, E.Mustafin. *Adaptation of the DCHAIN-SP code for mutual using with the SHIELD transport code.*
Cooling of the electronic board and of beam trap elements after irradiation with 209 MeV proton beam, 1 mkA, during 8 hours.

The first point on the time axis corresponds to one hour after the beam is turned off.
The dose rate for the electronic board and beam trap elements

To convert activity into dose rate at each time, the Tables of the conversion factors were used:

The GSF Tables have been calculated using the Monte Carlo codes EGS4 and SPHERE for photon and electron transport, and contain data for about 800 radioisotopes.

The conversion factors are given for the point source of photons and electrons, located in the air at the distance of 1 m from the irradiated object, which is the ICRU sphere H'(10) (tissue equivalent phantom, ∅=30 cm, depth 10 mm).

The conversion factors are tabulated in units of \(\text{mSv} \cdot \text{hour}^{-1} \cdot \text{GBq}^{-1}\). Multiplying the activity by the conversion factors, we get the contribution to the equivalent dose from the specific radioisotope. Summing contributions from all radioisotopes, we get the equivalent dose for given time of cooling.

Table 1. Equivalent dose (\(\mu\text{Sv/h}\)) as a function of the cooling time after 8 hours of irradiation

<table>
<thead>
<tr>
<th>Source of radiation</th>
<th>Time since the beam was turned off</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 hours</td>
</tr>
<tr>
<td>Electronic board</td>
<td>679</td>
</tr>
<tr>
<td>Rough estimation for elements of the beam trap</td>
<td></td>
</tr>
<tr>
<td>Target (graphite)</td>
<td>8.85\cdot10^4</td>
</tr>
<tr>
<td>Heavy concrete</td>
<td>1.18\cdot10^4</td>
</tr>
<tr>
<td>Borated polyethylene 1</td>
<td>64.9</td>
</tr>
<tr>
<td>Borated polyethylene 2</td>
<td>18.0</td>
</tr>
<tr>
<td>Iron sheet</td>
<td>98.4</td>
</tr>
</tbody>
</table>

For category A personnel, the maximal permissible dose is 50 mSv/year, i.e. 29.4 \(\mu\text{Sv/h}\) with 1700 hours work per year. Therefore, working with the electronic board may start one day after the end of irradiation.
Heat dissipation in the electronic board

Energy deposition in the electronic board for proton of energy 209 MeV is 6.52 MeV/proton.

With the board thickness of 0.7 cm and the beam diameter of 3 cm, the volume of the beam region in the board is 4.95 cm$^3$. The power of heat release in beam region is $1.32 \text{ MeV/(cm}^3\text{cdot proton)}$.

At beam current of 1 $\mu$A, the power of heat release is equal to: $Q=8.24 \times 10^{12} \text{ MeV/(cm}^3\text{cdot s)}$, or $Q=1.32 \text{ J/(cm}^3\text{cdot s)}$ or, $Q=0.552 \text{ J/(g\cdot s)}$, at the board material density $\rho=2.39 \text{ g/cm}^3$.

Taking the heat capacity of the board material $C \approx 0.7 \text{ J/(g\cdot°C)}$ (consisting 90% of silicon), we get estimation of the heating rate $Q/C \approx 0.8^\circ\text{C/s}$ in the beam region. At this heating rate, the melting point of silicon $\sim 1400 \degree\text{C}$ can be achieved in half an hour of irradiation.

Therefore, it is necessary to organize the beam scanning and/or take other measures: increase the beam cross section, reduce the beam current, design a cooling etc.
Neutron fluxes outside the accelerator tunnel

The accelerator tunnel is protected by the mound of 6 m thick ground. The attenuation of neutron flux was estimated with the relaxation length. The flux density $\varphi(x)$ of a collimated neutron beam behind a layer of matter of thickness $x$ is described by the exponential:

$$\varphi(x) = \varphi_0 \exp(-\Sigma \cdot x),$$

where $\Sigma$ is the macroscopic cross section.

The macroscopic cross section $\Sigma$ for standard chemical composition of ground as a function of neutron energy is shown in the plot below (chemical composition of ground includes 8 elements from O to Fe).

The minimal macroscopic cross section takes the value $\Sigma_{\text{min}}=0.0355 \, \text{cm}^{-1}$ at neutron energy of 209 MeV. At ground thickness of $x=600 \, \text{cm}$ the flux attenuation is equal to $e^{-\Sigma_{\text{min}} \cdot x}=5.46 \cdot 10^{-10}$ (the worst attenuation).

As shown above, the maximal flux of secondary neutrons from the trap is directed upward and equal to $2.2 \cdot 10^7 \, \text{n/cm}^2/\text{s}$ at beam current of 1 $\mu$A. At the worst attenuation of $5.46 \cdot 10^{-10}$ the neutron flux behind the mound is of $\sim 10^{-2} \, \text{n/cm}^2/\text{s}$, which is two orders of magnitude lower than the permissible level for a population. The neutron flux in the horizontal direction is two orders of magnitude lower.
Conclusion

As a result of simulation of the Stand for irradiation of electronic boards at maximal parameters of the proton beam - energy 209 MeV, current 1 µA - the following conclusions may be drawn:

1. In presence of the accelerator beam on the Stand, the integral fluxes of neutrons into the experimental hall are quite large: $5.5 \cdot 10^5$ n/cm$^2$/s in the horizontal direction and $2.2 \cdot 10^7$ n/cm$^2$/s into the upper hemisphere. Additional biological protection is required.

2. The dose rate from the electronic board one day after the end of irradiation is 27.5 µSv/h. For category A personnel, the maximum permissible dose is 50 mSv/year, i.e. 29.4 µSv/h with 1700 hours work per year. Therefore, working with the electronic board may start one day after the end of irradiation.

3. The heating rate of the electronic board in the beam region is high enough, of 0.8 deg/s. Therefore, it is necessary to organize scanning of the beam, and/or take other measures for decreasing the heating.

4. The fluxes of albedo nucleons from the beam trap to being irradiated electronic board are small and don't distort the effect of proton beam irradiation.

5. The existing earth mound above the accelerator tunnel is certainly enough to protect the surrounding space from secondary neutrons. The reserve is of two orders of magnitude and more.
Thank you for your attention!

http://www.inr.ru/shield/