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Low activation materials applicable to the IFMIF accelerator

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Abstract

The International Fusion Materials Irradiation Facility (IFMIF) is an intense neutron source for developing fusion materials. Stable and continuous operation is of primary importance. The radioactivity produced in the accelerator components due to the deuteron beam loss prolongs the cooling time and may pose a potential limit to the proposed availability of 70%. As such radioactivity is produced by deuteron beam loss and secondary neutrons with energy up to 50 MeV, the materials selection is important for minimizing the radioactivity after about one day cooling time. The major components of accelerator are selected by multiple engineering reasons, so the beam loss should be controlled to restricted areas and proper materials applied there. From an analysis of induced radioactivities in candidate materials, the beam loss along the linac needs to be reduced below ~5 nA/m. The arrangements and suitable materials for a scraper to realize the required beam loss limit are presented.

1. Introduction

A primary design specification for the IFMIF accelerator system is the requirement for 'hands-on' maintenance during its design lifetime, ~40 years [1]. 'Hands-on' means 'without requiring remote manipulators'. The accelerator components near the places where beam loss is anticipated have the possibility to become radioactive due to nuclear reactions between the lost beam, the secondary produced neutrons and the materials. In particular, losses of the deuteron beam would generate neutrons even in the low energy section. This results in the importance of the activation issue in the IFMIF (D^+ 40 MeV max) comparable to the proton beam with much higher energy. Fig. 1 shows the guideline of the beam loss at the major accelerator components estimated from the design requirements for the beam transmission up to the RFQ, and also the beam loss criteria tentatively borrowed from the FMIT design [2,3] (<3 μA/m along the accelerator and the high energy beam transport line and <10 μA at each bend magnet). Such criteria, which would require remote handling maintenance, are employed to keep a safety margin for the radiation shielding. We expect that the modern design techniques employed in the IFMIF reference design will result in much lower losses than were predicted for FMIT. The value, ~3 nA/m, for achieving hands-on maintenance is assigned as the goal for beam loss control in the IFMIF design. The important reactions producing the radioactive materials due to the beam loss at each part of the accelerator module are also summarized in Fig. 1. At the injector, about 15 mA D^+ of 0.1 MeV energy is lost before entering the RFQ and another 15 mA of D_2^+ and D_3^+ ions would be scraped off. Such lost ions are trapped at the surface of the equipment facing to the beam, subsequent ions produce ~2 MeV neutrons and tritium by the D(d,n) and D(d,p) reactions respectively. A similar process occurs at the entrance section of the RFQ in the course of the beam bunch formation stage and up to ~15 mA beam may be lost. The produced neutrons can activate the accelerator components when they are thermalized and captured. Therefore the following

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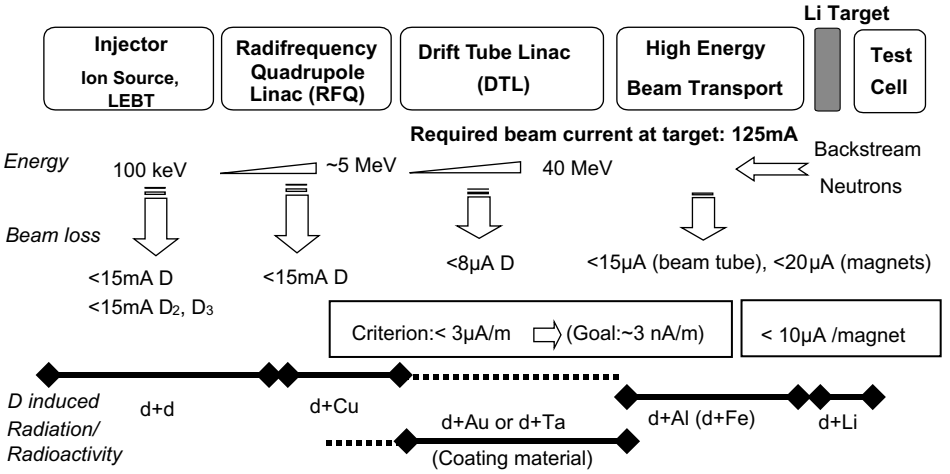

Fig. 1. Beam loss criteria and radioactivity of materials in the IFMIF accelerator components.

approach might be effective for suppressing such activation at the injector section:

(1) set up a specific point where most of the beam loss component will be trapped;
(2) replace the ion trapped materials with the new materials periodically, or continuously to restrict the accumulation of deuterium on their surface; and
(3) put neutron absorbing materials around the ion-trapping materials to reduce the thermal neutron flux around the accelerator components.

A possible approach for the downstream equipment where the passing beam energy becomes higher is to use a high-Z material coating on the surface to reduce the neutron production yield at the beam loss points, such as the gold plating on drift tubes proposed in the FMIT project.

In this report, the validity of the beam loss goal value is examined through the calculation of the activation and the resulting dose equivalent due to the beam loss. The results of the induced radioactivities for the selected materials, copper, tantalum and aluminum, are presented under a typical beam loss condition which can be scaled to the actual conditions. The dose equivalent is derived by assuming the typical beam loss condition which can be scaled to the actual condition. The dose equivalent is derived by assuming the typical cooling down time and the distance at which the equipment maintenance is performed, such as inspection or removal for repair. The effects of the possible choice of the materials and their compositions in the components are also examined. Finally the amount of beam loss acceptable in the specified cool down scenario is estimated.

2. Calculation method and results

The primary deuteron and the secondary neutron induced radioactivities are calculated using the IRACM code [4], which is developed to handle the isotope production yield due to the particles, n, p, d, α and some heavy ions. In this code the cross sections for n and d of the incident energy up to 150 MeV are available as ACSELAM data library [5]. The evaluated data are mainly derived from theoretical calculations and comparison with experimental data is necessary for the important reaction products to confirm the calculations. In this study, the three materials, copper, aluminum, and tantalum, are selected as the typical beam facing materials in the accelerator components.

2.1. Copper

Copper is the main element of the cavity wall and electrodes (vanes of RFQ and drift tubes of DTL) of the IFMIF accelerator and the conductors of the magnets. It is the most important element from the viewpoint of the production of radioactivities with lifetimes greater than several minutes, which might be a minimum threshold lifetime in considering the cool down time for the maintenance. The cross sections and the thick target yields of producing the radioactivities, ^{65}Zn (halflife, $T_{1/2} = 244.3$ d), ^{63}Zn ($T_{1/2} = 8.5$ m), ^{62}Zn ($T_{1/2} = 9.2$ h), ^{64}Cu ($T_{1/2} = 12.7$ h), ^{62}Cu ($T_{1/2} = 9.7$ m), ^{61}Cu ($T_{1/2} = 3.3$ h), are compared between the ACSELAM library and the experimental data to confirm the reliability of the data library. As an example, the results for the ^{65}Zn production are shown in Fig. 2. Although the individual data in the library have a systematical discrepancy with the experiments [6–10] due to the

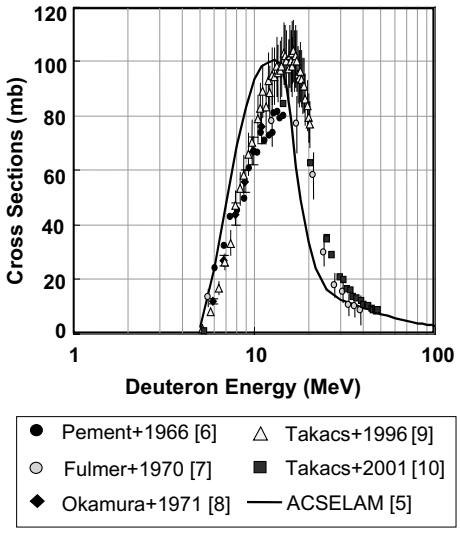

Fig. 2. Comparison of the ACSEAM data library and the experiments for the ^{65}Cu(d,2n)^{65}Zn reaction.

deficiency of the theoretical model, the effect on the overall accuracy for the dose equivalent becomes a limited one because it is obtained by the integration over the energy range up to 40 MeV and the summation over the various contributing reaction channels. The dose equivalent at the position of 1 cm distance from the radioactivity is estimated at various deuteron energies and cooling down times after 40 years irradiation of 1 μA beam on 1 cm^2 area, as shown in Fig. 3. The dose level during 40 years operation is always below this reference value. After 10 h cool down, the dose level would be less than 20 Sv/h. However, the radioactivity is typically produced at inner surface of drift tube walls, and the actual dose for the workers can be reduced by a factor of 10^{-1}–10^{-3} due to the attenuation in the tank structural wall (∼1 cm thick iron) with an additional local shield (several mm ∼ several cm thick lead) and the distance between the activated tube and the workers body (∼1 m). If the dose level of ∼10 μSv/h needs to be achieved for maintenance after 10 h cool down, the permitted beam loss in ∼40 MeV energy section, for which the irradiation area per meter is ∼10^3 cm^2 with a beam aperture radius of ∼1.5 cm, should be kept less than 5 ∼ 500 nA. A tentative guideline for the beam loss along the section with beam energy larger than 20 MeV should be 5 nA/m.

At the beam energy ∼12 and ∼7 MeV, the beam loss criteria are relaxed by a factor of 10 and 100, respectively. Therefore, the criteria for beam loss values can be increased to 20 and 50 nA/m at the sections with respective energy ranges 12–20 and 8–12 MeV.

2.2. Aluminum

For aluminum, used as the main component of beam tubes and chambers, the radioactivities, ^{22}Na ($T_{1/2} = 2.6$ y) and ^{24}Na ($T_{1/2} = 15.0$ h), are important from the viewpoint of accelerator system maintenance. The dose equivalent curves for Al are shown in Fig. 4. However, the data in the ACSELAM library for ^{27}Al(d,x)^{24}Na reaction indicated ∼1 order lower than the experimental data. This reaction is the only contribution to the total dose with cool down time ranging from 1 h to several tens hours, so that the result should be multiplied by 10 when the energy range is greater than 16 MeV. From this consideration, the dose level after 10 h cool down is similar to the Cu case in the highest energy section, so that the same beam loss criteria can be applied for Al too. For the lower energy part, the radioactivity in Al is much less than that in Cu and the radioactivity decays fast enough if the cool down time of 100 h is employed. The contribution of ^{26}Al ($T_{1/2} = 7.2 \times 10^5$ y) produced by secondary neutrons at beam transport line is ignorable because the fast neutron flux is low under the controlled beam loss condition.

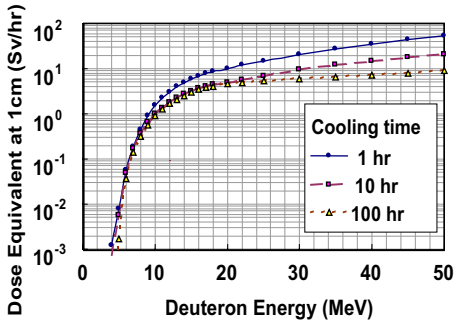

Fig. 3. Dose equivalent at 1 cm from the radioactivity produced by 1 μA beam loss for 40 years on copper calculated by IRACM code.

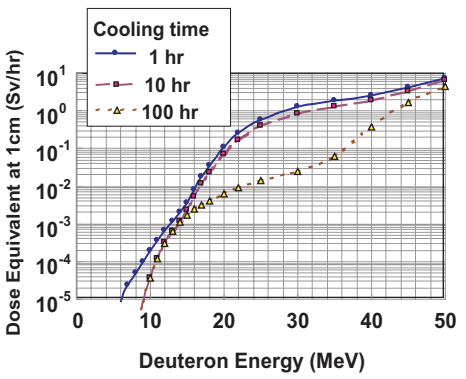

Fig. 4. Dose equivalent at 1 cm from the radioactivity produced by 1 μA beam loss for 40 years on aluminum calculated by IRACM code.

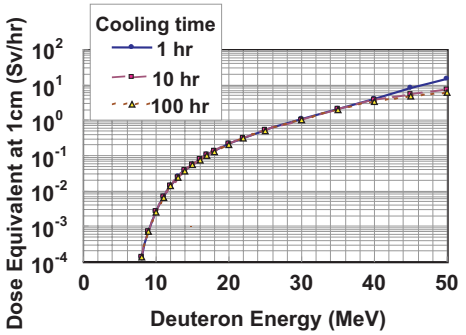

Fig. 5. Dose equivalent at 1 cm from the radioactivity produced by 1 μA beam loss for 40 years on tantalum calculated by IRACM code.

2.3. Tantalum, gold, lighter elements

Tantalum is a candidate material for the beam slit to scrape the beam halo component and also can be used as a coating to protect the beam facing materials from excessive production of excessive of radioactivity. Other high-Z materials, like Au, W, etc., or C are also useful for the same purpose but tantalum is the best from the viewpoint of less induced radioactivity and higher melting point. The dose curves for Ta are shown in Fig. 5; no difference in the various cool down times (1–100 h) in the energy range <40 MeV is seen because their decay is controlled by ^{182g}Ta ($T_{1/2} = 114.4$ d). The tolerance level for beam loss on Ta is larger than Cu and Al by a factor of 10, i.e. 50 nA $\sim$ 5 μA for 40 years, so that it is effective to use Ta for scraping the halo component of the beam.

The results for gold are similar to tantalum with a few differences: (1) the dose equivalent of Au at energy >20 MeV is about three times larger, (2) the decay of Au in the time range of 1–100 h is mainly controlled by ^{195}Hg ($T_{1/2} = 9.9$ h) and $\sim$100 h cool down time can reduce the dose equivalent by a factor of 5. A light element, like carbon, produces less radioactivity and the decay is faster than the above elements, however, it may produce more neutrons by the deuteron induced reactions, so that the use of C needs to pay attention to the neutron induced radioactivity around it.

3. Conclusions

The reliability of the database for the radioactivity of accelerator components is checked with some experimental data and discrepancies are found in microscopic cross sections, especially in the ^{27}Al(d,x)^{24}Na reaction. It is not so critical in case of the heavier elements for which the number of contributing channels is large and the errors can cancel out. The beam loss criteria for Cu and Al are estimated, from the calculated dose equivalent for 5 nA at a point (or 5 nA/m), Ed = 40 MeV, and after 40 years operation, by taking into account the smallest value of the attenuation factor for the radiation shielding scheme at maintenance time. For Ta, beam loss value is relaxed to 50 nA. As a conclusion, a guideline for the beam loss along the section with beam energy larger than 20 MeV is estimated to be 5 nA/m. The values can be increased to 20 and 50 nA/m at the sections with respective energy ranges 12–20 and 8–12 MeV.

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