

Simulation of induced radioactivity for a heavy ion medical machine

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Abstract: The radioactivity induced by carbon ions of the Heavy Ion Medical Machine (HIMM) was studied to assess its radiation protection and environmental impact. Radionuclides in the accelerator component, and in the cooling water and air at the target area, which are induced from primary beam and secondary particles, are simulated by FLUKA Monte Carlo code. It is found that radioactivity in the cooling water and air is not very important at the required beam intensity and energy that is needed for treatment, while radionuclides in the accelerator component may cause some problems for maintenance work and, therefore, a suitable cooling time is needed after the machine is shut down.

Key words: radioactivity, HIMM, heavy ion

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1 Introduction

Nowadays, radiation therapy is an important means of tumor treatment. More than 50% of all patients with localized malignant tumors are treated with radiation [1]. Many accelerators have been built for medical purposes. Heavy ion therapy is the most advanced of these medical treatments. This therapy started at the Bevalac facility of LBL in 1975 [2]. There are now four countries that have been practicing heavy ion therapy. Since 1993, the IMP (Institute of Modern Physics, Chinese Academy of Sciences) has researched the biological effects of radiation with middle energy heavy ions. In 2006, it started superficial tumor treatment of clinical research with an 80 MeV/u carbon ion beam. Two years later, deep treatment with higher energy heavy ion beam began [3]. In 2010, IMP decided to build a HIMM in Lanzhou, which is a special treatment device for carbon ion radiotherapy.

As a high-energy heavy ion accelerator, the induced radioactivity produced in the accelerator and its beam-line components may cause radiation on maintenance workers, make the disposal of activated components difficult, and have a certain radiation influence over the environment. Meanwhile, the induced radioactivity in the cooling water and air may affect not only the accelerator maintenance workers but also the public and the environment through release. In this work, radionuclides induced by HIMM and their environmental impact are studied.

Research on induced radioactivity may be traced

back to the early period when Curie and Joliot found the activation reaction in 1934 [4]. In recent years, improvements of the accelerator have meant that more kinds of particles, of a higher energy can be accelerated and, therefore, research on induced radionuclides of accelerators has continued [5–8]. As heavy ion therapy has been put into practice, more people have paid attention to the environmental impact caused by the radiation of heavy ion accelerator induced radioactivity. However, many of these reports were only very recently published [9, 10].

HIMM includes an ion source, a low energy beam transport line, an injector cyclotron, a middle energy beam transport line, a synchrotron (main accelerator), a high energy beam transport line, and four treatment rooms (Fig. 1). Carbon ions are accelerated to 7 MeV/u by the cyclotron and injected into the synchrotron through the intermediate energy beam transport line. The energy is then increased by the synchro-

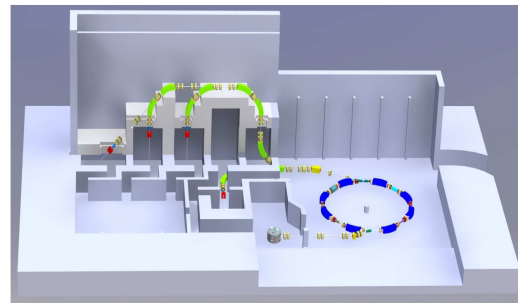


Fig. 1. Schematic diagram of the HIMM layout.

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ron from 80 MeV/u to 400 MeV/u, and delivered to the treatment room through the high energy beam line. The beam loss at the extraction position and treatment room will result in induced radioactivity of the HIMM. In this paper, the induced radioactivity of the accelerator component, and of the cooling water and air around the HIMM target area is studied with FLUKA code.

2 Simulation

The heavy ion accelerator induced radioactivity includes two parts: those induced by the primary ion beam, which mainly exist in the accelerator components and target, whose activity is larger and concentrated on the beam loss position; and, the radionuclides induced by secondary particles, which are widely distributed in the shielding material, air and cooling water, whose specific activity is very small. The radiation level of induced radioactivity depends on the accelerated ions, their energy, the beam intensity, the material irradiated, the running time of the accelerator, and so on.

In fact, not many materials are used in the construction of accelerators. The most important ones are iron, stainless steel, copper, aluminum and aluminum alloys, and various hydrocarbons. Since heavier target materials produce more radionuclides, copper is selected as the target material. FLUKA code [11, 12] is used in this work. The carbon ion energy is set to 400 MeV/u, the beam intensity is 1×10^8 pps, and the beam cross section diameter is 2 mm. The copper target is a cylinder of 5 cm in diameter and 10 cm in thickness, and its axis coincides with the beam-line, thus the thickness of target is enough to stop the primary beam. For calculation of radionuclides in cooling water, assuming that the pipe axis is the same as the copper target, its inner and outer radii are 20 cm and 22 cm, respectively, and it is 38 cm

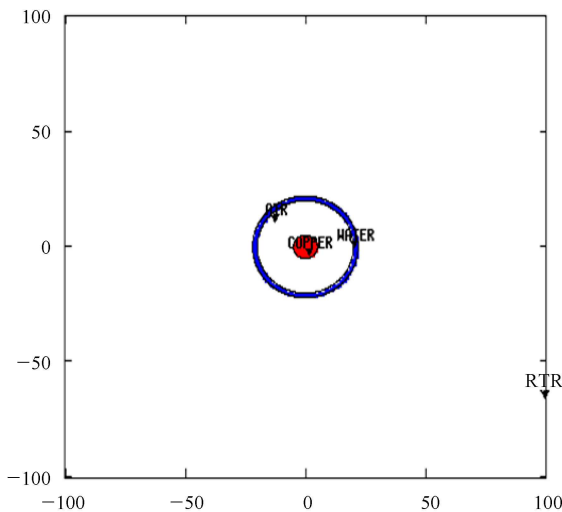


Fig. 2. (color online) A schematic diagram of calculation model.

long (Fig. 2). The size of the treatment room is 4 m×6 m×6 m, and it is filled with dry air (Fig. 3). The irradiated time is set to 30 d. The compositions of the each material are shown in Table 1.

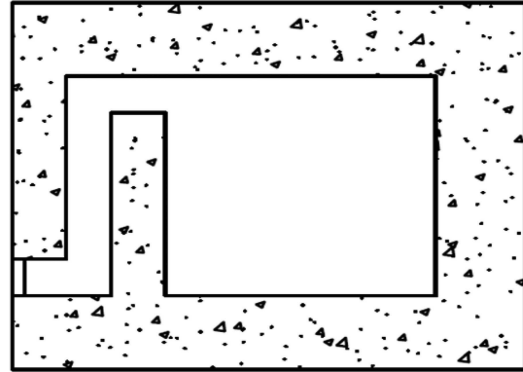


Fig. 3. A schematic diagram of the treatment room.

Table 1. The composition of each material.

| material | element | portion | density/(g/cm ³) |
|----------|---------|----------|------------------------------|
| copper | Cu | 1 | 8.9 |
| water | H | 0.111111 | 1 |
| | O | 0.88889 | |
| air | C | 0.000125 | 0.0012 |
| | N | 0.755267 | |
| | O | 0.231781 | |
| | Ar | 0.012827 | |

For a series of physical processes, such as spallation, neutron and γ capture, etc. a nuclear reaction can be produced when the carbon ion beam hits the copper target. The physical process is described by the PHYSICS card which is supplied by FLUKA. For nuclear reactions induced by neutron activation, the LOW-NEUT low energy neutron transport must be activated. The IRRPROFI and DCYTIMES card is used to describe the irradiation and cooling time of the target. Eventually, a RESNUCLE card is chosen as the detector, which can obtain radionuclides within the detector region.

3 Results and discussion

It can be seen from Fig. 4 that there are more than two hundred induced radionuclides in the copper target after irradiation. But in view of radiation protection, only a few radionuclides control the radiation field after irradiation. The important radionuclides for radiation protection are listed in Table 2. If there is more than one kind of radionuclide, then it is exemptible only if the sum of the ratio of activity to its exempt value of each kind of the radionuclide is less than 1 [13]. The sum of the ratio of activity to their exempt value is greater than 3500, so the activity of the copper target is high. After

Table 2. The activity of main radionuclides in a copper target.

| radionuclide | activity/Bq | $T_{1/2}$ | activity/exempt | radionuclide | activity/Bq | $T_{1/2}$ | activity/exempt |
|------------------|--------------------|-----------|-----------------------|------------------|-----------------------|------------|-----------------------|
| ^{64}Cu | 9.24×10^8 | 12.700 h | 9.24×10^2 | ^{46}Sc | 7.59×10^6 | 83.79 d | 7.59×10^0 |
| ^{65}Ni | 2.87×10^7 | 2.5172 h | 2.87×10^1 | ^{47}Ca | 2.28×10^5 | 4.536 d | 2.28×10^{-1} |
| ^{63}Ni | 2.86×10^5 | 100.1 a | 2.86×10^3 | ^{45}Ca | 9.23×10^5 | 162.61 d | 9.23×10^{-2} |
| ^{65}Zn | 5.92×10^5 | 244.26 d | 5.92×10^{-1} | ^{42}K | 1.21×10^7 | 12.36 h | 1.21×10^1 |
| ^{61}Co | 7.52×10^7 | 1.650 h | 7.52×10^1 | ^{40}K | 2.57×10^{-3} | 1.277E+9 a | 2.57×10^{-9} |
| ^{60}Co | 2.17×10^6 | 5.2714 a | 2.17×10^1 | ^{41}Ar | 1.84×10^6 | 109.34 min | 1.84×10^{-3} |
| ^{57}Co | 3.19×10^7 | 271.79 d | 3.19×10^1 | ^{37}Ar | 1.38×10^7 | 35.04 d | 1.38×10^{-1} |
| ^{56}Co | 3.20×10^7 | 77.27 d | 3.20×10^2 | ^{38}Cl | 4.32×10^6 | 37.24 min | 4.32×10^1 |
| ^{55}Co | 1.50×10^7 | 17.53 h | 1.50×10^1 | ^{35}S | 2.59×10^6 | 87.32 d | 2.59×10^{-2} |
| ^{59}Fe | 6.94×10^6 | 44.503 d | 6.94×10^0 | ^{33}P | 6.12×10^6 | 25.34 d | 6.12×10^{-2} |
| ^{55}Fe | 7.51×10^6 | 2.73 a | 7.51×10^0 | ^{32}P | 1.67×10^7 | 14.262 d | 1.67×10^2 |
| ^{52}Fe | 2.32×10^6 | 8.275 h | 2.32×10^0 | ^{31}Si | 5.00×10^6 | 157.3 min | 5.00×10^0 |
| ^{56}Mn | 4.69×10^7 | 2.5785 h | 4.69×10^2 | ^{24}Na | 3.92×10^6 | 14.959 h | 3.92×10^1 |
| ^{54}Mn | 1.44×10^7 | 312.3 d | 1.44×10^1 | ^{22}Na | 1.83×10^5 | 2.6019 a | 1.83×10^{-1} |
| ^{52}Mn | 5.08×10^7 | 5.591 d | 5.08×10^2 | ^{18}F | 5.52×10^6 | 109.77 min | 5.52×10^0 |
| ^{51}Mn | 2.47×10^7 | 46.2 min | 2.47×10^2 | ^{14}C | 1.22×10^1 | 5730 a | 1.22×10^{-6} |
| ^{51}Cr | 1.03×10^8 | 27.7025 d | 1.03×10^1 | ^{15}O | 2.08×10^6 | 122.24 s | 2.08×10^3 |
| ^{48}V | 7.34×10^7 | 15.9735 d | 7.34×10^2 | ^7Be | 1.05×10^6 | 53.12 d | 1.05×10^{-1} |
| ^{47}Sc | 1.69×10^7 | 3.3492 d | 1.69×10^1 | ^3H | 4.38×10^6 | 12.33 a | 4.38×10^{-3} |
| ^{48}Sc | 4.35×10^6 | 43.67 h | 4.35×10^1 | | | | |

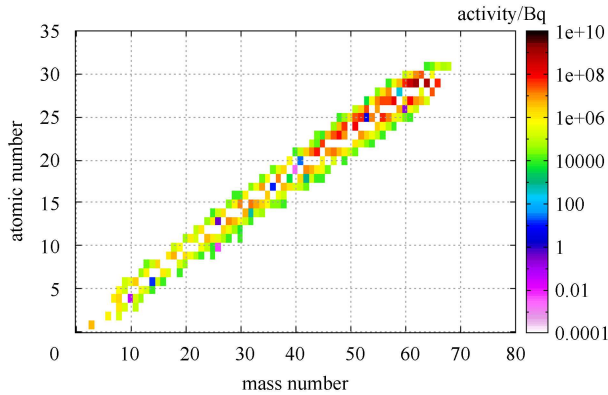


Fig. 4. (color online) The activity of radionuclides in copper target after irradiation.

irradiation, most radionuclides are short-lived, although the total activity of the copper target is strong (4.48×10^9 Bq). One hour later, the activity declines to about half of its original value (Fig. 5).

From the above calculation results, the kind of radionuclides in the copper target are found to be the largest of the three materials. This is due to the process of the nuclear reaction. Radionuclides in copper are induced by carbon ions and secondary particles with copper. An idealization heavy ion interaction model, which is known as Abrasion-Ablation model, was presented in detail by Günzert-Marx K [14].

The calculated air-borne radionuclides are shown in Table 3. ^3H , ^7Be , ^{15}O , ^{41}Ar , etc. are the most important radionuclides and they are mostly produced by the interaction of secondary neutron with air, ^3H , ^7Be are more interesting in radiation protection, other radionuclides are less important because of their shorter half-life or low yields. The harm of these radionuclides on human beings comes from beta and gamma irradiation,

and irradiation induced by inhalation. The total activity discharged to environment monthly in ventilation must be calculated. The assumption is as follows. The tunnel ventilation frequency is 2 h; the total activity within a dynamic ventilation cycle discharged to environment is equal to the total activity after two hours irradiation (A_2). So the total activity discharge to environment in one month is $A = A_2 \times 12 \times 30$. The instantaneous activity of ^3H , ^7Be after irradiation 2 h is 1.303 Bq and 29.68 Bq, respectively, so for one month the activity discharge is 469.08 Bq and 10684.8 Bq. This value is within the limit prescribed by the State [15]. According to Table 3, the total ratio of activity to their exempt value is less than 1 that is exempt; therefore, its hazard to the environment can be neglected.

Table 3. The activity of main air-borne radionuclides in treatment room.

| radionuclide | activity/Bq | $T_{1/2}$ | activity/exempt |
|------------------|-----------------------|------------|-----------------------|
| ^{41}Ar | 4.25×10^6 | 109.34 min | 4.25×10^{-3} |
| ^{37}Ar | 4.99×10^4 | 35.04 d | 4.99×10^{-4} |
| ^{38}Cl | 1.00×10^4 | 37.24 min | 1.00×10^{-1} |
| ^{36}Cl | 3.03×10^{-2} | 3.0E+5 a | 3.03×10^{-8} |
| ^{35}S | 8.46×10^3 | 87.32 d | 8.46×10^{-5} |
| ^{33}P | 2.24×10^4 | 25.34 d | 2.24×10^{-4} |
| ^{32}P | 4.60×10^4 | 14.262 d | 4.60×10^{-1} |
| ^{22}Na | 2.16×10^2 | 2.6019 a | 2.17×10^{-4} |
| ^{15}O | 5.09×10^6 | 122.24 s | 5.09×10^{-3} |
| ^7Be | 1.59×10^6 | 53.12 d | 1.59×10^{-1} |
| ^3H | 8.88×10^4 | 12.33 a | 8.88×10^{-5} |

Radionuclides in water come from neutron induced ^{16}O spallation, the activation results are listed in Table 4, ^3H and ^7Be are the most important radionuclides, their activities are 4.775×10^4 Bq and 9.17×10^5 Bq, respectively. Cooling water is used in a closed-circuit circulation system, and assuming a daily loss is 0.5%, so ^3H , ^7Be emissions in the environment for one month are

very low and are within the limits prescribed by the State [15].

The total activity will decrease rapidly just after the accelerator is shut down (Fig. 5). The total activity in the copper target will reduce to about 53% of its original after one hour, and the activity will reduce to one order of magnitude in air and cooling water, and then the decay of the total activity becomes slow. Many short-lived nuclides will be finished within 5 h. Regardless of the type of activation material, the radioactive decay law with the cooling time is similar. The final straight portion in Fig. 5 is only the long-lived radionuclides contribution. After cooling for half an hour, the total activities will reduce to about 59% of the accelerator shut down, thus half an hour cooling time is essential after a long running time.

Table 4. The activity of main radionuclides in cooling water.

| radionuclide | activity/Bq | $T_{1/2}$ | activity/exempt |
|-----------------|--------------------|-----------|-----------------------|
| ^{15}O | 2.25×10^7 | 122.24 s | 2.25×10^{-2} |
| ^{14}C | 4.88×10^1 | 5730 a | 4.88×10^{-6} |
| ^7Be | 9.17×10^5 | 53.12 d | 7.17×10^{-2} |
| $^3\text{H-3}$ | 4.77×10^4 | 12.33 a | 4.77×10^{-5} |

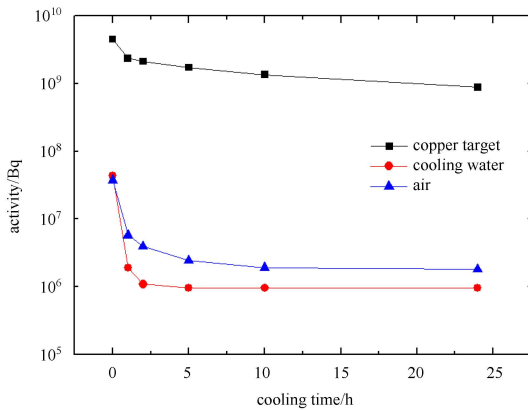


Fig. 5. The decay of total activity of induced radioactivity.

Figure 6 gives the dose rate around the target. At 20 cm from the target surface, assuming that a worker operates the target half an hour after the machine is shut down, 10 times a year, each time for half an hour, then the total accumulated dose will be 10.3 mSv a year.

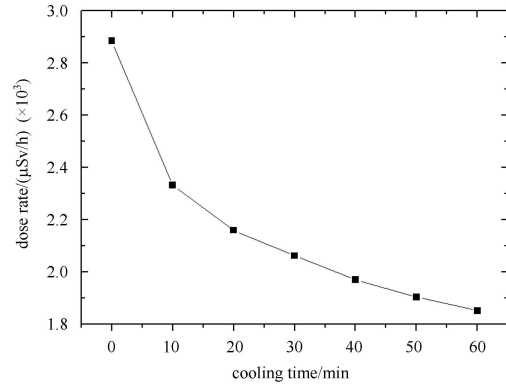


Fig. 6. Dose rate at 20 cm from copper target surface after the accelerator shutdown.

4 Summary

In this paper, the radionuclides induced by HIMM are investigated with FLUKA code. It is found that the air and cooling water activation effect on the environment or the staff is not very important, while the components of accelerator induced radioactivity has some influence on the maintenance personnel. One hour after the accelerator is shut down, its activity can be reduced to about from 10% to 53% of the original; therefore, a period of cooling time just after the machine is shut down will greatly reduce the expose dose to maintenance workers. Some radiation protection measures may be needed after a long running time since long-lived radionuclides are accumulated by a considerable amount. The data obtained in this work are vital for fundamental radiation protection and environmental impact assessment.

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