Radioactive Isotope Induced by Beam Loss in Particle Accelerator for Heavy-Ion Inertial Fusion*)

Suzuka FUJITA, Hideki TENZO[1)], Kazumasa TAKAHASHI,
Toru SASAKI and Takashi KIKUCHI

Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan
[1)]*National Institute of Technology (KOSEN), Kagawa College, Mitoyo, Kagawa 769-1192, Japan*

(Received 30 November 2020 / Accepted 14 January 2021)

We investigated radiation distributions, fluences, generation rates, and radioactive isotopes induced by heavy-ion impact into a vacuum vessel wall for a particle accelerator in the heavy-ion inertial fusion (HIF). Numerical results showed that the radiation management should be considered for neutrons and photons during the HIF system operation. Compared to the detailed numerical simulation, estimations in total reaction cross-sections and threshold kinetic energy for interaction in the Coulomb barrier were expected to provide criteria as a safer side for radiation management in the HIF accelerator. The activation and the isotopes generated by the interaction between the heavy-ion and the wall material were obtained from the calculation results, which showed that the generation rate and the variation of the generated isotope increased with the incident kinetic energy of the heavy-ion beam. The calculation results also indicated that the management of radioactive materials is important for the HIF accelerator system's safe operation.

Keywords: heavy-ion inertial fusion, particle accelerator, activation, radiation distribution, radioactive isotope, beam loss, heavy-ion beam

DOI: 10.1585/pfr.16.2404022

1. Introduction

Nuclear fusion power generation has abundant fuel resources and is being explored and developed as a sustainable power generation method for human society. Furthermore, advantages in the nuclear fusion power generation are rich in fuel resources, no global warming gas emissions, and no high-level radioactive waste.

Heavy-ion inertial fusion (HIF) is one of the methods to realize a thermonuclear fusion system. The HIF system requires high-power and high-current heavy-ion beams produced by a particle accelerator [1–4]. The ion trajectories with high kinetic energy are controlled well, although there are a few uncontrollable particles, such as halo particles, which are the particles escaping from the beam core. It is difficult to completely avoid undesirable particle losses into the vacuum vessel wall and induce radiation damage in the particle accelerators. Thus, the problem of radiation damage induced by the heavy-ion impact is unavoidable in realizing future HIF power plants. Therefore, it is important to maintain the radiation damage within a manageable level throughout the large site area of the HIF system.

We investigated the radiation damage induced by the ions in the particle accelerator complex for the HIF system because the large site area of the HIF accelerator is a unique problem in the HIF power plant. Radio activation is different at each part of the accelerator complex because the kinetic energy of the ions has a broad energy range from MeV to GeV. It is known that the injection of heavy ions into stainless steel produces different radioactive isotopes depending on the incident energy [5].

In our previous study [6], the ratio of the kinetic energy of the heavy-ion to the Coulomb barrier was determined, and the total reaction cross-section between the heavy-ion and the wall material of the vacuum vessel was estimated. The kinetic energy threshold for the interaction with the Coulomb barrier was estimated as 3.5 MeV/u, and the maximum cross-section was 12 MeV/u for Pb ions. We demonstrated the schematic layouts of HIF accelerator concepts with the total reaction cross-section and indicated the expected site area for the potential radiation safety management.

In this study, we investigated the radioactive isotopes generated by the heavy-ion impact into the vacuum vessel wall for the HIF accelerator because not only the threshold kinetic energy and the cross-section for the nuclear reaction but also the species of the radioactive isotopes generated by the impact of the heavy ions are key issues for the maintenance and the safety from the viewpoint of radioactivation.

author's e-mail: fujita_s_0707@stn.nagaokaut.ac.jp

*) This article is based on the presentation at the 29th International Toki Conference on Plasma and Fusion Research (ITC29).

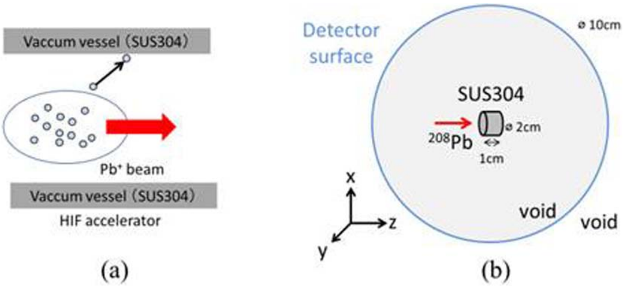

Fig. 1 Schematic view of heavy-ion impact in particle accelerator (left) and computational box for interaction between Pb ion beam and SUS304 target (right).

2. Calculation Condition for Ion Impact in HIF Accelerator

We investigated the species and the radioactivity of the isotopes produced by the heavy-ion impacts using the particle transport calculation code PHITS ver.3.20 (Particle and Heavy-ion Transport code System) [7], which is a general-purpose Monte Carlo particle transport simulation code developed under collaboration between JAEA and RIST, etc.

Pb^+ is a candidate for a heavy-ion beam in the HIF. Stainless steel (SUS304) is used as the primary material for the vacuum vessel of the particle accelerator.

A few ions (halo particles) escaping from the beam core may impact the vacuum vessel (SUS304) wall of the particle accelerator, as shown in Fig. 1 (a). We simulated that the $^{208}Pb^+$ ions were injected into a cylindrical SUS304 target with a thickness of 1 cm placed in the center of a spherical calculation region (vacuum), as shown in Fig. 1 (b).

3. Calculation Results

3.1 Radiation distribution

We investigated the radiation distribution induced by the interactions between the ions and the SUS304 target using the PHITS. Figure 2 shows the typical spatial distributions of the incident ions, neutrons, and photons when the kinetic energy of the incident ion was 48 MeV/u. The figures (a), (b), and (c) show the distributions in the *x*-*z* plane, and the figures (d), (e), and (f) show the distributions in the *x*-*y* plane. No electrons or protons were generated.

The distributions of the incident ion $^{208}Pb^+$ are shown in Fig. 2 (a) for the *x*-*z* plane and Fig. 2 (d) for the *x*-*y* plane. As shown in these figures, the ^{208}Pb beam was stopped by the target of 1 cm thickness.

The distributions of the neutrons and photons induced by the interactions between the incident ion and the target are shown in Figs. 2 (b) and (c) for the *x*-*z* plane and Figs. 2 (e) and (f) for the *x*-*y* plane, respectively. The neutrons and photons were generated and scattered outside the target. It was found that the neutrons were scattered mainly in the positive direction (behind the target) in the *z*-axis from Fig. 2 (b). On the other hand, the photons were scattered in all directions.

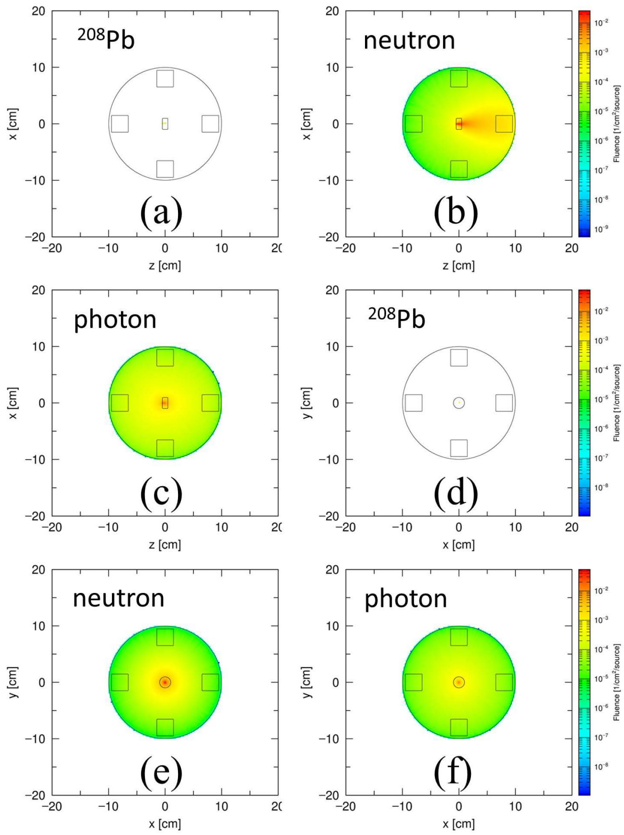

Fig. 2 Spatial distributions of incident ion, neutron, and photon for 48 MeV/u of ^{208}Pb into SUS304 target.

3.2 Fluence induced by impact between ion and wall

We calculated the fluence as a function of the incident ion energy of the radiation induced by the interaction between the Pb^+ ions and the SUS304 target using PHITS, and compared it with the threshold kinetic energy for the Coulomb barrier and the total cross-section.

We estimated the ratio of the Coulomb barrier and the kinetic energy of the incident heavy-ion, and 3.5 MeV/u was the threshold kinetic energy [6]. We also calculated the total reaction cross-section at each kinetic energy between the Pb^+ ion and the wall material, Cr, Fe, and Ni, which are the main constituent elements of SUS304 [6].

Figure 3 shows the fluence and the total reaction cross-section as a function of the incident kinetic energy of the Pb^+ ion and the threshold kinetic energy for the interaction in the Coulomb barrier. As shown in Fig. 3, the fluence increased over kinetic energy of 7 MeV/u. Thus, it is expected that the vacuum vessel of the HIF particle accelerator is activated when the kinetic energy exceeds 7 MeV/u.

3.3 Generation rate of isotopes

We have considered the radioisotopes produced by the

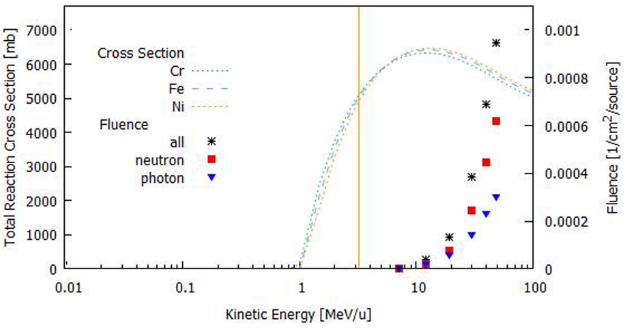

Fig. 3 Fluence (points) and total cross-section (dashed curves) as a function of kinetic energy. The vertical line (yellow) indicated the threshold kinetic energy for the interaction in Coulomb barrier.

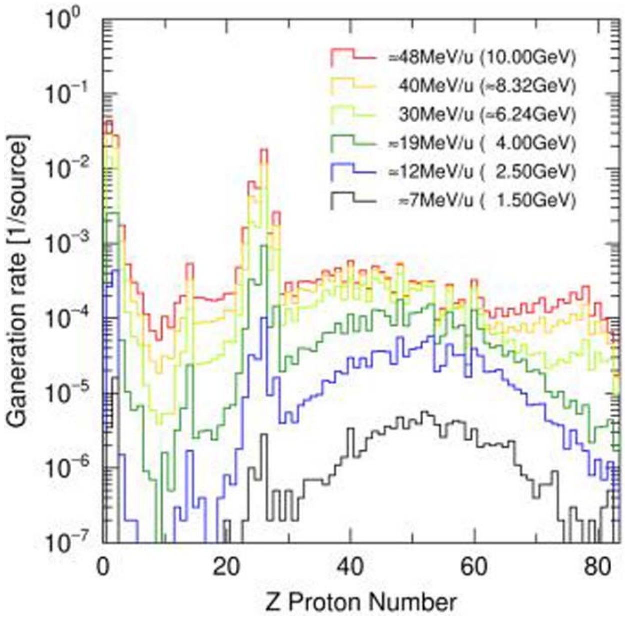

Fig. 4 Generation rate as a function of proton number.

interaction between the Pb^+ ion and the wall material of the vacuum vessel. Figure 4 shows the generation rate as a function of the proton number at each incident kinetic energy of the Pb^+ ion. The kinetic energy of the incident ion corresponded to the energy range for the HIF accelerator [1].

The incident ion with higher kinetic energy produced a higher generation rate. The highest generation rate was for the proton number of 1. A large generation rate was also found for the proton number around 26. It is expected that radioactive isotopes were generated by activating stable isotopes such as in SUS304.

3.4 Nuclide chart of generated isotopes

The nuclide chart of the isotopes generated by the ^{208}Pb impact on the SUS304 target at each incident kinetic energy is shown in Fig. 5. The kinetic energy of the incident ion corresponded to the energy range for the HIF accelerator [1].

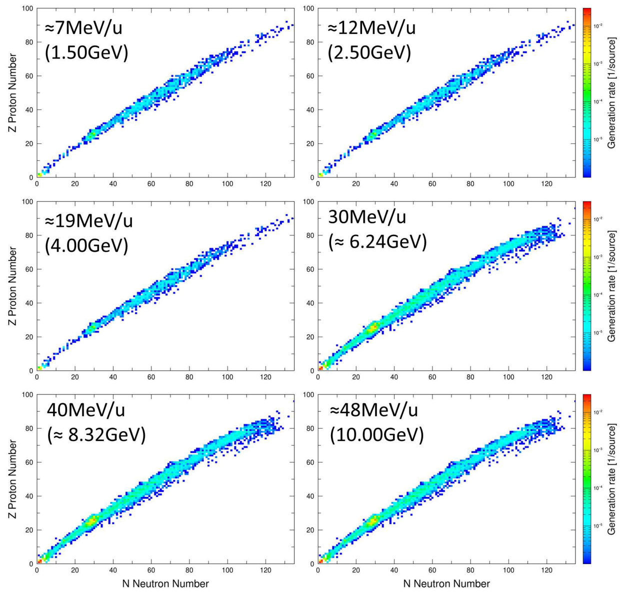

Fig. 5 Nuclide chart for generated isotope at each incident kinetic energy.

Although the lowest ion energy in the HIF accelerator is approximately 2 MeV for the ion source, no generated isotopes were observed below 1 GeV of the incident kinetic ion energy. Various isotopes were produced with an increase in the incident ion energy. The higher incident kinetic energy of the ^{208}Pb ion produced neutron-rich isotopes. For this reason, it is expected that activation will occur in the higher incident kinetic energy of the ^{208}Pb ion.

3.5 Generated radioactive isotopes

We summarized the half-life and the generation rate of radioactive isotopes generated by the ^{208}Pb ion impact on the SUS304 target. Table 1 shows a summary of the kinetic energy of the incident ions at 48 MeV/u.

As shown in Table 1, gas-state isotopes at room temperature such as Hand He were generated. There were radioactive isotopes for Fe, Cr, Mn, and it is considered that they were produced from stable isotopes as ^{56}Fe, ^{52}Cr, ^{55}Mn in the stainless steel.

4. Discussion

In this study, we investigated the radiation damage induced by the Pb^+ ions for the HIF particle accelerator complex because the large site area for the HIF accelerator is a unique problem in the HIF power plant.For this reason, we discussed the summary of the calculated resultsfrom the viewpoint of radiation and radioactivity in this section.

As shown in Fig. 2, the incident ion was stopped in the target with a kinetic energy of 48 MeV/u, which is expected to have the highest kinetic energy for the HIF accelerator complex [1]. It was also found that electrons and protons were not generated to impact the vacuum vessel

Table 1 Generated radioactive isotopes (by ordering generation rate).

	Isotope	Half-life	Generation rate (1/source)
1	^{3}H	12.32 y	0.013370
2	^{55}Fe	2.744 y	0.002680
3	^{54}Mn	312.20 d	0.001388
4	^{51}Cr	27.704 d	0.000899
5	^{53}Mn	3.74E6 y	0.000706
6	^{50}Cr	1.3E18 y	0.000530
7	^{57}Co	271.74 d	0.000508
8	^{6}He	806.7 ms	0.000389
9	^{56}Mn	2.5789 h	0.000373
10	^{50}V	2.65E17 y	0.000369

wall. On the other hand, the neutrons and photons were scattered outside the vacuum vessel of the particle accelerator. As a result, the radiation protection for the neutron and photon should be considered during the accelerator operation in the HIF system.

As shown in Fig. 3, the fluence was estimated as a function of the incident kinetic energy of the Pb^{+} ion. The results were compared with previous results [6] in the total reaction cross-section and the threshold kinetic energy for the interaction in the Coulomb barrier. Compared to the calculation result for the fluence, the threshold kinetic energy estimation is expected to be a safer side. The kinetic energy at the maximum reaction cross-section corresponded to the rising point of the incident kinetic energy for the fluence. Consequently, the total reaction cross-section and the threshold kinetic energy for the interaction in the Coulomb barrier are useful as rough estimations from the viewpoint of the site area classification for radioactive safety management.

On the other hand, detailed information on the radioactivation and the isotopes generated by the interaction were obtained using the PHITS, as shown in Figs. 4 and 5. Figures 4 and 5 show that the generation rate and the variation of the generated isotope increased with an increase in the incident kinetic energy. From the viewpoint of radioactivation, it is easy to manage the ion source of the HIF accelerator system because no generated isotope was observed below 1 GeV of the incident kinetic ion energy.

It was expected that activation occurred in the higher incident kinetic energy of Pb ions because the higher incident kinetic energy of Pb ion produced the neutron-rich isotopes, as shown in Fig. 5. Table 1 shows the generated radioactive isotope ordering the generation rate with an incident kinetic energy of 48 MeV/u. Since ^{3}H (Tritium) was observed with the maximum generation rate for the interaction between the incident Pb ion and SUS304, it is considered to be remarkable in radiation safety management in the HIF accelerator system.

5. Conclusion

In this study, we investigated the radiation distribution, fluence, generation rate, and radioactive isotopes induced by the heavy-ion impact into the vacuum vessel wall for the particle accelerator in the HIF. The numerical simulation results showed that radiation management should be considered for the neutron and photon during the accelerator operation in the HIF system.

The detailed numerical simulation using the PHITS showed that the estimations in the total reaction cross-section and the threshold kinetic energy based on the interaction in the Coulomb barrier provide safer side criteria for radiation management in the HIF accelerator.

The radioactivation and the isotopes generated by the interaction between the heavy-ion and the wall material were obtained using the PHITS. The generation rate and variation of the generated isotope increased with the incident kinetic energy of the heavy-ion.

It was expected that the activation would occur in the higher kinetic energy of the incident ion because the higher incident kinetic energy of heavy-ion produced the neutron-rich isotopes from the calculation result.

The result showed the Tritium generation due to the interaction between the Pb ion and SUS304. This should be noted for radiation safety management in the HIF accelerator system.

Consequently, the above results by combining the site layout of the particle accelerator, the rough estimations, and the detailed numerical approach provide useful information for radiation safety management at each stage in the HIF power plant because the large site area for the HIF accelerator is crucial in the HIF power plant.

[1] J.J. Barnard *et al.*, Nucl. Instrum. Methods Phys. Res. A **415**, 218 (1998).
[2] C.R. Prior *et al.*, Proc. EPAC1998, 323 (1998).
[3] K. Horioka, Matter Radiat. Extremes **3**, 12 (2018).
[4] K. Takayama *et al.*, Phys. Lett. A **384**, 126692 (2020).
[5] T. Nakamura, Radiat. Prot. Environ. **35**, 111 (2012).
[6] S. Fujita *et al.*, High Energy Density Phys. **37**, 100848 (2020).
[7] T. Sato *et al.*, J. Nucl. Sci. Technol. **55**, 684 (2018).