RESIDUAL ACTIVITY INDUCED BY HIGH-ENERGY HEAVY IONS IN STAINLESS STEEL AND COPPER*

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Abstract

The activation of accelerator structures due to beam-losses is an intensity-limiting problem for existing (SNS or RHIC) and planned (LHC or FAIR) high-power accelerator facilities. While beam-losses of 1 W/m are recognized as a tolerable level for proton machines, the beam-loss tolerances for high-energy heavy-ion accelerators have not yet been quantified. Experimental study of the residual activity induced by uranium beams in stainless steel and copper was performed at GSI Darmstadt. The results of the experiments were compared with simulations by Monte Carlo particle transport codes FLUKA and SHIELD. After validation of the codes, the simulations of the residual activity induced in copper and stainless steel were performed for projectiles from proton to uranium. It was found that the isotope inventory contributing over 90% to the total activity does not depend on the projectile species; it depends only on the target material. The activity induced by an ion beam of the unit beam-power scales down with increasing ion mass. The beam-loss criteria for different projectiles were established.

INTRODUCTION

Activation of the accelerator components due to beam-losses becomes an important issue for high-energy accelerators. Distributed and localized beam losses during the normal machine operation are one of the major sources of activation [1]. Quantification of residual activity induced by lost particles is important to evaluate radiation hazards to personnel during "hands on" maintenance. While beam-losses distributed uniformly along the beam line on the level of 1 W/m (equivalent to 6.24×10^9 1 GeV protons/m/s) are presently accepted for proton machines as a threshold for "hands on" maintenance [2], a beam-loss tolerance for high-energy heavy-ion accelerators has not yet been quantified.

Our studies have been focused on experimental determination and simulations of residual activity induced by high-energy heavy ions in the most common accelerator construction materials, stainless steel and copper. The simulations were performed with FLUKA and SHIELD codes. The main goal of the study was establishing a scaling law for induced activity as a function of ion mass and estimation of the beam-loss criteria for different projectiles from proton up to uranium at energies from 200 MeV/u up to 1 GeV/u.

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EXPERIMENTAL STUDY

The experiments were performed at GSI Darmstadt as a preparatory work for constructing the FAIR facility. Copper and stainless steel targets were irradiated by 120 MeV/u, 500 MeV/u and 950 MeV/u 238-U beams [3, 4]. The main task of the study was: (1) to identify the isotopes with dominating contribution to the residual activity, (2) to measure depth-profiles of residual activity of induced isotopes and (3) to determine the contribution of individual isotopes to the residual activity. Gamma-ray spectroscopy was used to identify the isotopes as well as to determine their depth-profiles and residual activities. The targets were constituted as a set of foils with various thicknesses. The total target activity for each isotope in the case of 120 MeV/u and 500 MeV/u experiment was determined from the full-assembly target measurements [3], whereas the activities induced by 950 MeV/u uranium beam were obtained by integration of the depth-profiles [4]. The data collected in these experiments can be used to verify, improve and complete the physical models and data libraries of pertinent simulation codes.

MONTE CARLO SIMULATIONS

Validation of the Simulation Codes

Monte Carlo codes FLUKA and SHIELD were used to simulate the experiments and to investigate consistency of the results. Comparison of experimental and calculated data is presented in Fig. 1.

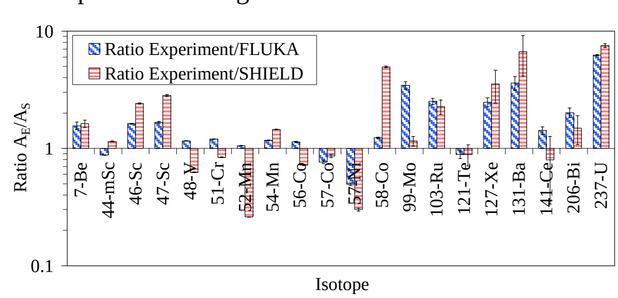

Figure 1: Ratio A_E/A_S for the isotopes with dominating contribution to the residual activity in stainless steel irradiated by 950 MeV/u 238-U ions. A_E is the experimentally measured activity and A_S is the activity calculated by FLUKA and SHIELD.

It can be seen that the discrepancies between measured and calculated values for individual isotopes vary from factor 0.26 to 7.53. The ratio of the experimentally measured total induced activity to the total activity calculated by FLUKA is 1.0986 ± 0.0029, which is a very good agreement. The ratio of the experimentally measured total induced activity to the total activity calculated by SHIELD is 0.6145 ± 0.0031, which means that SHIELD overestimates some isotopes with significant contribution to the total residual activity.

Simulation of the Residual Activity

After validation of the codes, FLUKA and SHIELD were used for simulation of residual activity and establishing a scaling law for tolerable beam-loses as a function of ion mass. The target materials were again stainless steel and copper. The assumed target geometry was a cylinder of 20 cm in diameter, 60 cm long. It represents bulky accelerator structures like a magnet yoke. The simulations were performed for projectiles 1-H, 4-He, 12-C, 20-Ne, 40-Ar, 84-Kr, 132-Xe, 197-Au and 238-U at energies from 200 MeV/u up to 1 GeV/u. The assumed beam profile was a Gaussian distribution with 1 σ = 0.25 cm. The simulated beam intensity was 10^{10} particles per second and the targets were assumed to be irradiated continuously for 3 months. The residual activity was calculated at different time-points after the end of irradiation: immediately, 1 day, 1 week, 2 months, 1 year and 10 years. A standard deviation of the FLUKA and SHIELD calculations ranged from 0.04 % to 0.81 % and from 0.10 % to 0.84 %, respectively. It was found that the isotope inventory contributing over 90 % to the total activity does not depend on the projectile species, but it depends on the target material and projectile energy.

As an example, results of the simulations of residual activity induced by 1 GeV/u and 200 MeV/u primary ions in stainless steel are shown in Figs. 2 and 3, respectively. The activities are normalized to the unit beam-power of 1 W delivered to the target. This normalized activity is decreasing with increasing primary-ion mass. That is why heavy ions induce less activity per unit beam-power compared to protons. The normalized activity decreases also with decreasing energy of primary ions.

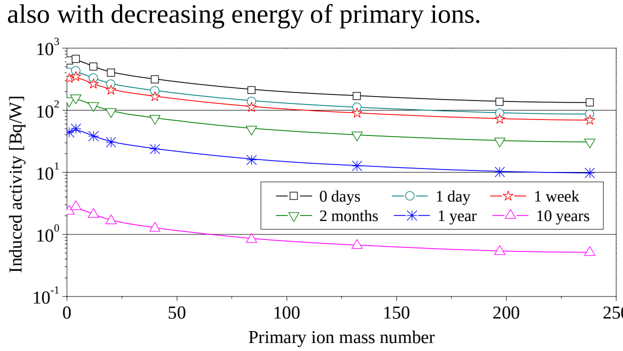

Figure 2: Activity per watt induced in stainless steel by different primary ions at 1 GeV/u calculated by FLUKA .

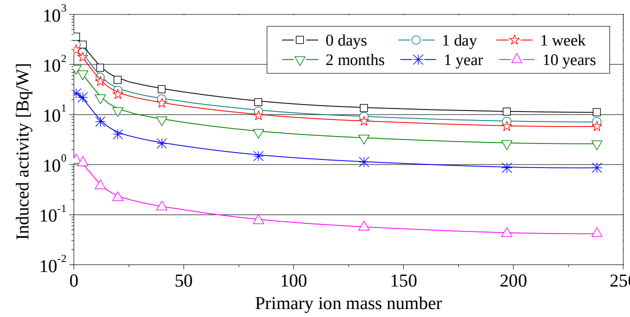

Figure 3: Activity per watt induced in stainless steel by different primary ions at 200 MeV/u calculated by FLUKA.

The decrease of the normalized activity can be explained by the fact that the heavier ions are stopped by Coulomb interaction with the target electrons and have a lower probability of interaction with target nuclei [5].

Probability of Nuclear Interaction

The formulas of Ref. [5] were used to calculate the probability of the nuclear interaction of a primary ion with the target material. At first, it is necessary to know the range and the mean free-path of the primary ion. The range *R* of the primary ions was calculated by SRIM code. The mean free-path λ can be expressed by Eq. 1:

$$\lambda = \frac{A_t}{\rho N_A \sigma} \tag{1}$$

where A_t is the mass number of the target material, ρ is the density of the target material, N_A is the Avogadro constant, σ is the total cross-section of nuclear interaction and is given by Eq. 2:

$$\sigma = \pi r_0^2 \left(A_t^{1/3} + A_p^{1/3} + a \frac{A_t^{1/3} A_p^{1/3}}{A_t^{1/3} + A_p^{1/3}} - c \right) \left(1 - \frac{B_C}{E_K} \right) \tag{2}$$

where $r_0 = 1.1 \times 10^{-15}$ m, $a = 1.85$, A_t and A_p are the mass numbers of the target material and the primary ion, respectively, parameter c depends on energy, however we can assume a constant $c = 2$ in the energy region from 100 MeV/u to 1 GeV/u with accuracy of about 10 %. E_K is the kinetic energy of the primary ions and B_C is the Coulomb barrier. The probability of nuclear interaction P is then given by Eq. 3:

$$P = 1 - \exp(-R/\lambda) \tag{3}$$

The values of the probability of nuclear interaction in copper for all projectiles in the energy range 200 MeV/u – 1 GeV/u are presented in Tab. 1. It can be seen, that the probability is decreasing with increasing mass of the primary ion and with decreasing projectile energy. It means that the primary ions at lower energies and with higher mass number are mostly stopped by Coulomb interaction with the target electrons and only a minor part of the beam interacts with the target nuclei because the mean free-path of these isotopes is much higher compared to the range. In contrast, the probability of nuclear interaction of protons and lighter nuclei such as 4-He at energy 1 GeV/u is almost one hence almost 100 % of the beam interacts with the target nuclei.

Table 1: Probability of nuclear interaction in copper.

E [MeV/u]	200	400	600	800	1000
1-H	0.24	0.58	0.81	0.92	0.97
4-He	0.37	0.76	0.93	0.98	1.00
12-C	0.21	0.52	0.75	0.88	0.94
20-Ne	0.16	0.41	0.63	0.78	0.88
40-Ar	0.12	0.34	0.54	0.69	0.80
84-Kr	0.09	0.26	0.43	0.58	0.69
132-Xe	0.08	0.23	0.38	0.51	0.63
197-Au	0.08	0.20	0.33	0.46	0.57
238-U	0.07	0.20	0.33	0.46	0.56

Beam-loss Criteria

For the estimation of the heavy-ion beam-loss tolerance, the accepted beam-loss tolerance of 1 W/m for protons was scaled using the ratio of the normalized activity induced by 1 GeV protons to the normalized activity induced by other projectile of interest at given energy. Although the normalized activity induced by 1 GeV protons is slightly different from the normalized activity induced by protons at lower energy, 1 GeV protons were taken as a reference in order to get a universal criterion. Simulations showed that 1 GeV/u uranium ions induce 5 times less activity per watt compared to the 1 GeV protons and 200 MeV/u uranium ions induce 58 times less activity per watt compared to the 1 GeV protons. Therefore, the tolerable beam-loss could be 5 W/m for 1 GeV/u uranium beam and 58 W/m for 200 MeV/u uranium beam. Other particles were treated in the same manner and results are plotted in Fig. 4 (stainless steel) and Fig. 5 (copper).

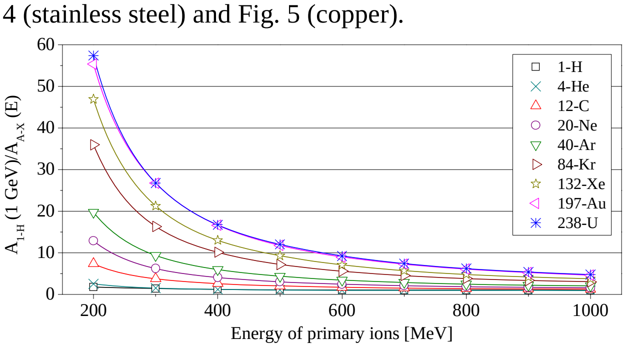

Figure 4: Scaling factor for the beam-loss tolerance as a function of projectile energy. A_{1-H}(1GeV) is the normalized activity induced by one 1 W of 1 GeV proton beam, A_{A-X}(E) is the normalized activity induced by 1 W of ion beam of interest at given energy. The activities are calculated by FLUKA immediately after the end of irradiation in stainless steel.

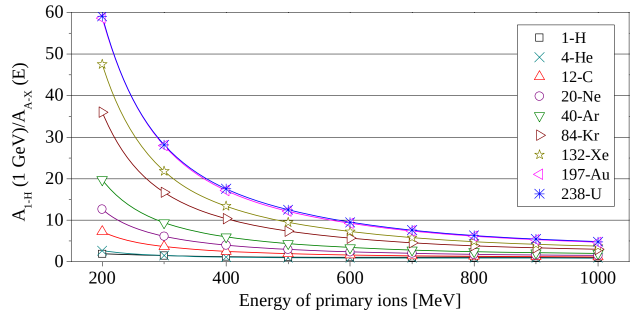

Figure 5: Scaling factor for the beam-loss tolerance as a function of projectile energy. A_{1-H}(1GeV) is the normalized activity induced by one 1 W of 1 GeV proton beam, A_{A-X}(E) is the normalized activity induced by 1 W of ion beam of interest at given energy. The activities are calculated by FLUKA immediately after the end of irradiation in copper.

CONCLUSIONS

Experimental study of the residual activity induced by uranium ions in stainless steel and copper was performed at GSI Darmstadt. The experimental results were compared with simulations by Monte Carlo codes FLUKA and SHIELD. The comparison showed that FLUKA and SHIELD are valid codes for the activation studies. Residual activities were calculated for different projectile species for the assessment of the beam-loss criteria. The tolerable beam-losses were specified for heavy ions by scaling the existing value for protons. The scaling yields the beam-loss tolerances of 5 W/m for 1 GeV/u uranium beam and 58 W/m for 200 MeV/u uranium beam. The data collected in this work can serve for an assessment of tolerable beam-loss levels at high-energy heavy-ion accelerators, which is important to evaluate radiation hazards to personnel.

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