BEAM-LOSS CRITERIA FOR HEAVY-ION ACCELERATORS AND ACTIVATION OF DIFFERENT MATERIALS*

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Abstract

Assessment of the radiation hazards from activated accelerator components due to beam-losses is a serious issue for high-energy hadron facilities. Important radiation-safety principle ALARA (As Low As Reasonably Achievable) calls for minimizing exposure to people. That is why the uncontrolled beam-losses must be kept on the reasonable low level. The beam-losses below 1 W/m are considered as a tolerable for "hands-on" maintenance on proton accelerators. The activation of the heavy-ion accelerators is in general lower than the activation of the proton machines. In our previous work, we estimated the "hands-on" maintenance criteria for heavy ions up to uranium in stainless steel and copper by scaling the existing criterion for protons. It was found out that the inventory of the isotopes and their relative activities do not depend on the primary-ion mass but depend on the target material. For this reason in the present work the activation of other important accelerator construction materials like carbon, aluminium and tantalum was studied using the FLUKA code.

INTRODUCTION

Activation of accelerators due to uncontrolled beam losses during normal operation is an important issue especially for high-energy hadron accelerators [1-4]. The residual activity induced by lost beam particles is a dominant source of exposure to personnel and one of the main access restrictions for "hands-on" maintenance [1].

Quantification of the residual activity provides fundamental information that can be used in several ways: (1) to specify the tolerable beam losses in the machine, (2) to optimize the choice of construction materials, or (3) to estimate the necessary "cooling" time after turning off the beam. All these three measures are important with respect to the reduction of personnel exposure.

The well known available information is that activation caused by uncontrolled beam losses uniformly distributed along the beam line on the level of 1 W/m can be accepted for high-energy proton accelerators as tolerable to ensure the "hands-on" maintenance [5]. The effective-dose rate in the vicinity of the activated accelerator components then should not significantly exceed 1 mSv/h for a typical operating period of an accelerator followed by a reasonable "cooling down" time before the "hands-on" maintenance (100 days irradiation / 4 hours cooling / 30 cm distance) [6-8]. The beam-loss criteria for heavy-ion accelerators were specified by scaling the 1 W/m criterion for protons [8-10].

In the frame of the FAIR project (Facility for Antiproton and Ion Research) [11] extensive experimental studies [12-14] and Monte Carlo simulations [8-10] of the residual activity induced by high-energy heavy ions in copper and stainless steel were performed at GSI Darmstadt. The simulations were performed by FLUKA [15, 16] and SHIELD [17, 18] codes. It was shown that the induced residual activity decreases with increasing primary-ion mass and with decreasing energy [8-10]. Besides that it was found out that the isotope inventory and their relative activities depend on the target material.

The results presented in this paper follow the previous studies [8-10] and give information about the residual activity induced in other materials: carbon, aluminium and tantalum. These materials are important for the construction of collimators [19, 20] and in addition aluminium also for the construction of beam pipes [21].

BEAM-LOSS CRITERIA FOR HEAVY-ION ACCELERATORS

FLUKA and SHIELD codes were used for simulation of the residual activity induced by various projectiles in two target configurations representing: (1) a beam pipe of an accelerator and (2) a bulky accelerator structure like a magnet yoke, a magnet coil or a collimator. The purpose of the simulations was to compare heavy ions with protons [8-10]. The target materials were stainless steel (beam pipe and bulky target) and copper (bulky target) representing the most common construction materials used for basic accelerator components. The assumed stainless-steel composition was C (0.07%), Mn (2.0%), Si (1.0%), Cr (18%), Ni (9.5%), and S (0.03%) in addition to iron (stainless steel 304). The simulations were performed for ^{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 residual activity and the effective-dose rate at the distance of 30 cm from the beam-pipe outer surface were calculated at different time points [8]. The activity was scored by both codes whereas the dose rate only by FLUKA.

Beam-Loss Criteria for Beam Pipes

The assumed beam-pipe geometry was a 10 m long tube made of stainless steel, 10 cm inner diameter, 2 mm wall thickness. The glancing angle between the incident beam particles and the inner surface of the beam pipe was 1 mrad. The irradiation time was 100 days. The beam

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pipe was irradiated by 1 W/m of beam particles. The beam particles were distributed uniformly along the beam line as shown in Fig. 1.

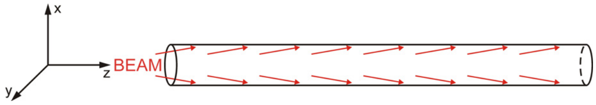

Figure 1: A model of the beam-pipe irradiation.

It was found that the inventory of isotopes with a dominating contribution to the total activity as well as their relative activities (with respect to the total activity) do not depend on the projectile species [8]. This can be explained by the fact that the isotopes are produced mostly by secondary particles rather than by the primary projectiles, as confirmed also experimentally [12-14].

Since the inventory of the isotopes and their relative activities are very similar for all projectiles, the time evolution of the activity during and after irradiation can be described by means of a generic curve that is independent from the projectile mass [8].

The residual activity was calculated at several time points after the end of irradiation. It was found out that the activity induced by 1 W/m of beam particles is decreasing with increasing ion mass. It is also decreasing with decreasing energy [8-10]. The same trend was observed for the effective-dose rate.

Such decrease of the activity can be explained by the fact that the heavy ions at lower energies are stopped mostly by Coulomb interaction with the target electrons and only a minor part of them interacts with the target nuclei. In other words, the Coulomb stopping range of these particles is shorter compared to their mean-free path of nuclear interaction. In contrary, protons and light ions have their ranges longer than the mean-free path [8, 22].

So far, it was found out that: (1) inventory of the isotopes induced in the stainless-steel beam pipe does not depend on the projectile species, (2) time evolution of the induced activity correlates to the generic curve, and (3) the activity induced by 1 W/m of beam particles is decreasing with increasing ion mass and with decreasing energy. These facts allow us to introduce a scaling law for heavy-ion beam-loss tolerances based on the accepted criterion of 1 W/m for protons. For this purpose, we define the *normalized activity* as the activity induced by unit beam power of 1 W at given time representing the lost beam particles hitting the accelerator structures. In the case of the beam-pipe geometry, these lost beam particles are assumed to be distributed uniformly along the beam pipe. The scaling factor is then obtained as the ratio of the normalized activity induced by 1 GeV proton taken as a reference in order to get a universal criterion, to the normalized activity induced by the beam of interest.

Simulations of the beam-pipe activation showed that normalized activity induced by uranium ions is about 12 times lower at 1 GeV/u, 23 times lower at 500 MeV/u, and almost 75 times lower at 200 MeV/u compared to 1 GeV protons. Therefore the tolerable beam losses for uranium beam could be 12 W/m at 1 GeV/u, 23 W/m at 500 MeV/u, and 75 W/m at 200 MeV/u. Other particles were treated in the same manner and results are plotted in Fig. 2. The same results are valid also for the effective-dose rates.

The FLUKA simulations were cross-checked with simulations performed by the independent Monte Carlo code SHIELD. The main purposes of this comparison were code/code benchmarking and investigation of a possible influence of the 100 MeV/u threshold for heavy-ion inelastic interactions in the FLUKA code: the heavy ions below this value are excluded from the simulation of the activation process. The results of the SHIELD simulations are presented also in Fig. 2. It can be seen that except for the beam energy of 200 MeV/u, the results are very similar. In case of the 200 MeV/u beam energy, the beam-loss criterion calculated by FLUKA is less strict than those calculated by SHIELD. This discrepancy is very likely caused by the 100 MeV/u threshold for heavy-ion interactions in FLUKA, since the discrepancy at higher beam-energies is smaller [8].

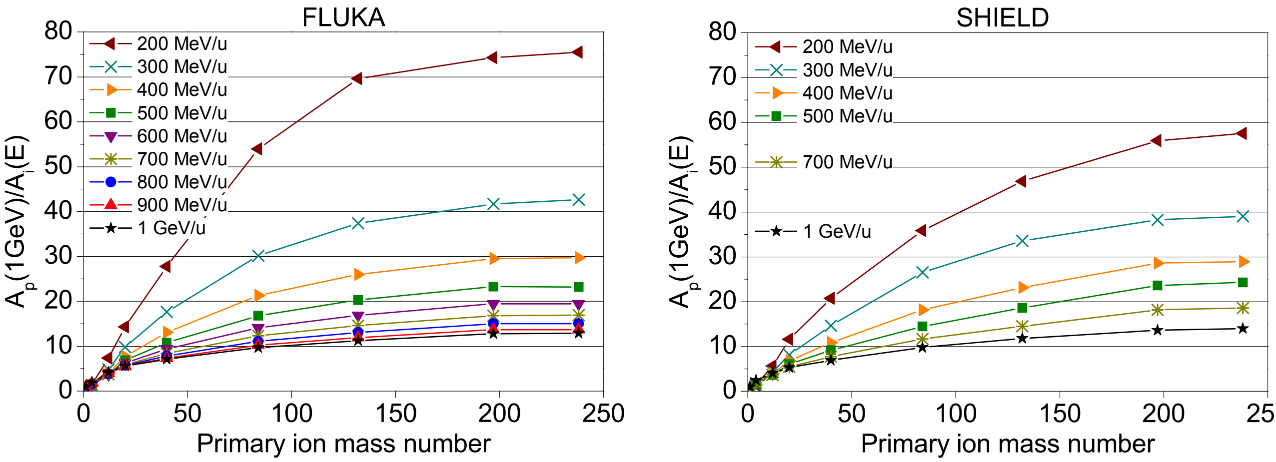

Figure 2: Scaling factor for the beam-loss criteria in the beam pipe as a function of primary ion mass. The scaling factor is represented by the ratio of the normalized activity induced by 1 GeV proton beam, A_p(1GeV), to the normalized activity induced by the beam of interest at given energy, A_i(E). The activities were calculated by FLUKA (left) and SHIELD (right) 4 hours after the end of irradiation.

Beam-Loss Criteria for Bulky Structures

Besides the beam pipe, accelerators contain also bulky structures. For this reason, FLUKA and SHIELD simulations of the activity induced by various projectiles were done also for a bulky target. The target materials were stainless steel and copper. The simulations were performed for the same projectiles as for the beam pipe. The assumed geometry of the bulky target was a full-material cylinder of 20 cm in diameter, 60 cm long. In this case the beam particles were impacted to the basement of the cylinder perpendicularly to its surface (see Fig. 3).

Figure 3: A model of the bulky-target irradiation.

Similarly to the beam pipe, the inventory of the isotopes induced in the bulky target and their relative activities do not depend on the projectile species. However, a well-pronounced dependence on the target material was observed (see Fig. 4).

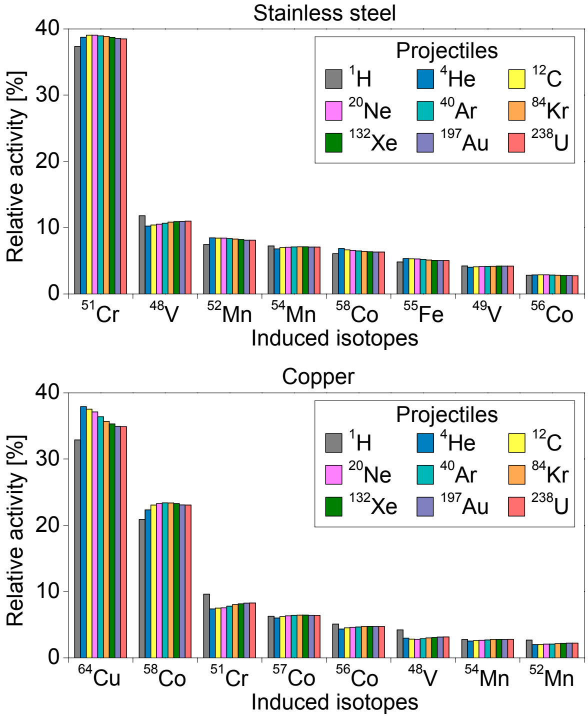

Figure 4: Isotope inventory and their relative activities 1 day after the end of irradiation induced by 1 GeV/u projectiles from proton up to uranium in stainless steel and copper bulky target calculated by FLUKA.

The normalized activity induced in the bulky target is again decreasing with increasing ion mass but significantly less than in case of the beam pipe. The beam-loss criteria for heavy ions in case of the bulky accelerator structures are then more strict than in case of the beam pipes. For example, the tolerable beam-losses for uranium beam could be 5 W/m at 1 GeV/u, 12 W/m at 500 MeV/u and 60 W/m at 200 MeV/u. In general, the scaling factor for the criteria depends on the target thickness [8]. The thin-wall beam-pipe exhibits significant leakage of the heavy-ion projectiles break-up nucleons [23] from the wall at small angles, which decreases the induced activity. Their contribution to the beam-pipe activation is missing and the activity is lower than in case of the bulky target [8].

On the contrary to the beam pipe, there is no such discrepancy between FLUKA and SHIELD at 200 MeV/u in the bulky target. The reason can be that the activity induced by primary particles compared with the activity induced by secondary particles is higher in case of the beam pipe than in case of the bulky target [8].

Although the inventory of induced isotopes and their relative activities in stainless steel and copper bulky target are different (see Fig. 4), the ratio of the normalized activity induced by protons to the normalized activity induced by heavy ions is almost the same in both materials [8]. This is due to the fact that normalized activities change similarly with the change of the target material, hence keeping the ratio almost constant.

DEPENDENCE OF THE RESIDUAL ACTIVITY ON THE TARGET MATERIAL

Comparison of the Stainless Steel with Copper

It was shown in Fig. 4 that the isotope inventory and their relative activities strongly depend on the target material. In case of stainless steel and copper this fact does not have an influence to the beam loss criteria which are almost the same for both materials. Even the absolute values of the normalized activities induced in the stainless steel and copper targets are similar. For example, ratio of the normalized activity induced in stainless steel to the normalized activity induced in copper by 1 GeV/u projectiles, vary from factor 0.6 to 2.0 at different time points after irradiation: immediately, 4 hours, 1 day, 1 week and 2 months (see Table 1). Note that 4 hours after irradiation the activities induced in stainless steel and copper target are very close to each other.

Table 1: Stainless steel to copper ratio of the normalized activities induced by 1 GeV/u projectiles at different time points after irradiation.

	0 h	4 h	1 d	1 w	2 m
^{1}H	0.6	0.9	1.4	1.9	1.5
^{4}He	0.6	0.9	1.5	2.0	1.7
^{12}C	0.6	0.9	1.5	2.0	1.7
^{20}Ne	0.6	0.9	1.6	2.0	1.7
^{40}Ar	0.6	0.9	1.6	2.0	1.7
^{84}Kr	0.6	0.9	1.6	2.0	1.6
^{132}Xe	0.6	0.9	1.6	2.0	1.6
^{197}Au	0.6	0.9	1.6	2.0	1.6
^{238}U	0.6	0.9	1.6	2.0	1.6

However this is not likely to be the case for some other materials. The isotope inventory especially the target activation products induced in materials with low atomic mass-number is considerably smaller than in stainless steel or copper [24]. The normalized activity induced in such materials is then expected to be lower than for stainless steel and copper. In contrary, there is large variety of isotopes induced in materials with the high atomic mass-number [24]. Consequently, the normalized activity should be higher than in stainless steel or copper.

Activation of Carbon, Aluminium and Tantalum

FLUKA simulations of the residual activity induced in the bulky target were performed for other common accelerator-construction materials: carbon, aluminium (low mass-number) and tantalum (high mass-number). The assumed geometry of the bulky target was again a cylinder of 20 cm in diameter, 60 cm long. The target was irradiated with the same nine projectiles and the residual activities were calculated at the same time points after irradiation as for stainless steel and copper.

It was found out that for the examined materials the inventory of the isotopes induced in the targets and their relative activities again do not depend on the projectile species. The decreasing of the normalized activity with increasing ion mass and decreasing energy was observed. As expected, the dependence of the isotope inventory on the target material was confirmed.

Stainless steel and copper are dominating materials of the accelerator structure and only a few components in the accelerator lattice are made of carbon, aluminium or tantalum. For this reason an introduction of the beam-loss criteria in terms of "W/m" for these materials is not reasonable any more. Instead of that we simply compare the normalized activities (induced by unit beam power of 1 W) in different materials. The comparison is expressed as the ratio of the normalized activity induced by 1 GeV proton beam in stainless steel, $A_{p\rightarrow ss}(1\mathrm{GeV})$, to the normalized activity induced by the beam with the energy of interest in given material, $A_{i\rightarrow m}(E)$. The normalized activities were calculated 4 hours after irradiation.

The normalized activity induced in the stainless-steel target by 1 GeV protons was taken as a reference value. Stainless steel was chosen because it is the most common construction material of accelerators and 4 h are agreed in the accelerator community as a reasonable ‘‘cooling down’’ time before the ‘‘hands-on’’ maintenance [6-8]. Although the stainless-steel composition might have an influence to the induced activity, this factor affects significantly only the activity of the low-energy neutron products [8]. However, in the case of activation induced by high-energy projectiles (over 100 MeV/u) the activity of the low-energy neutron products is much lower than the activity of the products of other nuclear-reactions (spallation, fragmentation, etc.). That is why the total activity is not affected significantly by the composition of the stainless-steel material [8].

Simulation showed that for the carbon target irradiated by uranium ions the ratio $A_{p\rightarrow ss}(1\mathrm{GeV})/A_{i\rightarrow m}(E)$ is equal to 29 at 1 GeV/u, 58 at 500 MeV/u, and 230 at 200 MeV/u. The results for aluminium are similar to the results for carbon. The ratio is equal to 33 at 1 GeV/u, 70 at 500 MeV/u, and 233 at 200 MeV/u. The ratio for tantalum is significantly lower than in case of carbon or aluminium and is only 1 at 1 GeV/u, 2 at 500 MeV/u and 10 at 200 MeV/u (see Fig. 5).

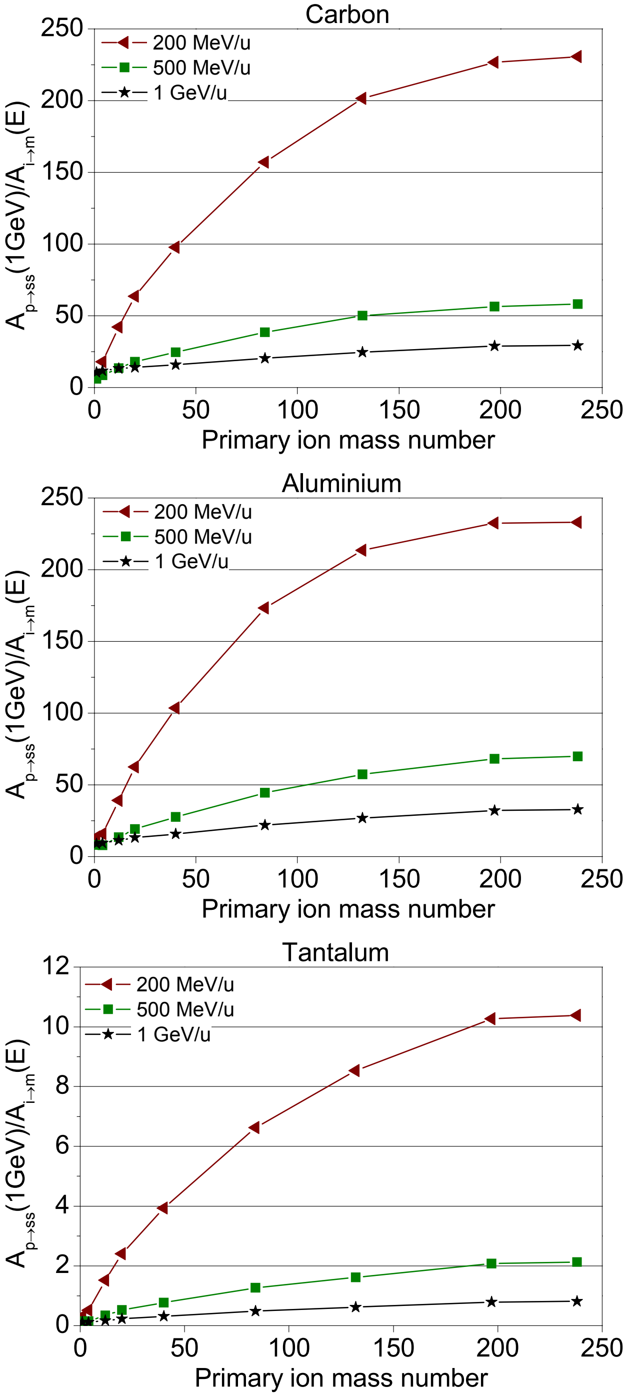

Figure 5: Ratio of the normalized activity induced by 1 GeV proton beam in stainless steel, $A_{p\rightarrow ss}(1\mathrm{GeV})$ to the normalized activity induced by the beam with the energy of interest in given material: carbon (top), aluminium (middle) and tantalum (bottom), $A_{i\rightarrow m}(E)$. The normalized activities were calculated 4 h after irradiation.

Besides that it was found out that the ratio of the normalized activities for carbon, aluminium and tantalum strongly depends on the ‘‘cooling down’’ time (see Table 2). This is due to different isotope inventory and their relative activities compared to the stainless steel. Consequently, the time evolution of the activity in carbon, aluminium and tantalum significantly differ from the stainless steel or copper which results in different ratio of the normalized activities for different time-points.

Table 2: Ratio of the normalized activities induced by 1 GeV proton beam in stainless steel (reference) to the normalized activity induced by the uranium beam in carbon, aluminium and tantalum. The ratio of the normalized activity was calculated at different time points after the end of irradiation.

1 GeV/u	0 h	**4 h**	1 d	1 w	2 m
C	7.2	**29**	27	24	20
Al	13	**33**	53	85	61
Ta	0.8	**0.8**	0.9	1.0	0.7
500 MeV/u	0 h	**4 h**	1 d	1 w	2 m
C	16	**58**	58	56	49
Al	30	**70**	115	212	170
Ta	2.2	**2.1**	2.5	2.7	1.8
200 MeV/u	0 h	**4 h**	1 d	1 w	2 m
C	80	**231**	236	257	251
Al	111	**232**	372	728	770
Ta	11.3	**10.4**	12.2	13.5	8.7

CONCLUSIONS

The beam-loss criteria for high-energy heavy-ion accelerators were specified for the beam-pipe geometry and the bulky-target geometry. Simulations showed that in the most common accelerator construction materials (stainless steel and copper), the inventory of the induced isotopes and their relative activities do not depend on the projectile species and energy but strongly depend on the target material. For this reason, a study of the activation of other accelerator construction-materials (carbon, aluminium and tantalum) was performed using FLUKA code. It was found out that the ratio of the normalized activity induced by 1 GeV proton beam in the stainless steel target (reference) to the normalized activity induced by the uranium beam in carbon and aluminium target is similar: 29 and 33 at 1 GeV/u, 58 and 70 at 500 MeV/u, and 230 and 233 at 200 MeV/u, respectively. The ratio of the normalized activities in tantalum bulky target is much lower: 1 at 1 GeV/u, 2 at 500 MeV/u and 10 at 200 MeV/u. The ratio was calculated for the normalized activities 4 hours after irradiation. Significant dependence of the ratio on the ‘‘cooling down’’ time was observed for all three materials.

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