

New results on the beam-loss criteria for heavy-ion accelerators

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Abstract

Activation of high-energy heavy-ion accelerators due to beam losses is a serious issue for accelerator parts like collimators, magnets, beam-lines, fragment separator targets, etc. The beam losses below 1 W/m are considered as tolerable for “hands-on” maintenance in proton machines. In our previous studies, the FLUKA2008 code has been used for establishing a scaling law expanding the existing beam-loss tolerance for 1 GeV protons to heavy ions. This scaling law enabled specifying beam-loss criteria for projectile species from proton up to uranium at energies from 200 MeV/u up to 1 GeV/u. FLUKA2008 allowed nucleus-nucleus interactions down to 100 MeV/u only. In this work, we review our previous results and extend activation simulations to lower energies with the help of the new FLUKA version, namely FLUKA2011. It includes models for nucleus-nucleus interactions below 100 MeV/u. We also tried to expand the scaling law to lower energies. This, however, needs further studies, because the heavy-ion-induced nuclide composition starts deviating from the proton-induced nuclide composition at energies below 150 MeV/u.

Introduction

Activation of accelerator components and their environment due to the beam losses during normal machine operation is not negligible. It is important to diminish them as much as possible; even they can never be totally eliminated. Activation of the accelerator components has an impact on hands-on maintenance of the machine and high level of residual activity may lead to access restrictions in some machine areas [1-3]. Beam losses may also damage or reduce lifetime of radiation-sensitive components of the accelerator. They also may alter material properties such as strain resistance, magnetic susceptibility, break-down voltage, etc., which influences proper functioning of accelerator elements made of these materials. Quantification of the residual activity can provide a key to specify tolerable beam losses and/or to optimise the choice of the construction materials. Analysis of the activation products (nuclides, their life-times and characteristics of the emitted radiation) is necessary in order to calculate the “cooling” time needed to keep the personnel exposure below radiation safety limits after the accelerator shut-down.

The lost beam particles interact with construction materials of the accelerator in several ways. The most important interactions are high-energy inelastic hadron interactions, neutron capture and photonuclear reactions. Important sources of activation are protons, neutrons and target fragments. Previous activation experiments and measured depth-profiles of residual activity pointed secondary particles as the main source of activation [4-7]. The FLUKA2008 calculations confirmed that the target fragments were the dominant source of activation in the case of high-energy heavy ions. They are produced independently from the projectile mass [7]. However, the projectile

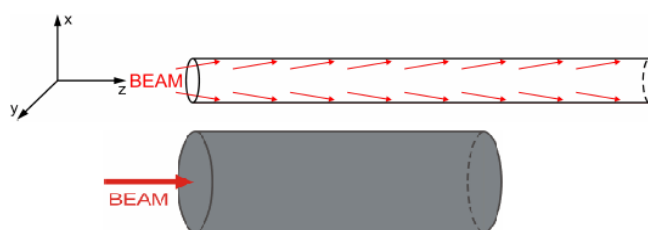
fragments can play an increased role in the case of lower beam energies. This contribution should depend on the projectile species.

A set of activation experiments and Monte Carlo simulations have been performed at GSI Helmholtzzentrum für Schwerionenforschung GmbH Darmstadt in the frame of preparation works for the FAIR (Facility for Antiproton and Ion Research) project [8]. The paper presents new simulation results obtained with FLUKA2011.2b.5. The new simulations were used to revise the previous beam-loss criteria [4]. The main difference between the old and new simulations concerns the energy threshold for the nucleus-nucleus interactions, which is below 100 MeV/u in FLUKA2011.2b.5 [9,10].

A summary of the previous studies

One of the first attempts to set a beam-loss criterion for high-energy heavy ions was based on FLUKA2008 simulations validated with dedicated activation experiments [4-7]. Those simulations were done for two target geometries representing a beam-pipe and a bulky target (see Figure 1). Stainless steel and copper were chosen as target materials frequently used for magnet yokes, coils, etc. Target activation was simulated for different projectiles (^1H , ^4He , ^{12}C , ^{20}Ne , ^{40}Ar , ^{84}Kr , ^{132}Xe , ^{197}Au and ^{238}U) at different energies from 200 MeV/u up to 1 GeV/u. The activities were normalised to the unit beam power of 1W delivered permanently during 3 months. The activity was calculated at several time points from the beginning of irradiation, through the end of irradiation up to 10 years after the end of irradiation. Results of the simulations were cross checked with experimental data [11-14]. Analysis of the simulated data showed that partial relative activities of the nuclides with dominating contribution to the total activity practically did not depend on the projectile mass. Generally, the total induced activity depended on energy and mass of the projectiles, as well as on the composition of the target material [4]. The total induced residual activity decreased with increasing projectile mass and with decreasing projectile energy [5-7].

Figure 1. Geometrical model of a beam-pipe (upper) and a bulky target (lower) irradiation [4]



Results based on the FLUKA2008 simulations

Simulations of the beam-pipe activation showed that normalised activity induced by uranium ions was 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. The same results were obtained from calculated effective-dose rates [4].

The normalised activity induced by uranium ions in the bulky target was about 5 times lower at 1 GeV/u, 12 times lower at 500 MeV/u, and almost 60 times lower at 200 MeV/u compared to 1 GeV protons. Therefore, 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.

Influence of the 100 MeV/u interaction threshold of FLUKA2008

Independent simulations were performed by another Monte Carlo code – SHIELD that takes into account production of radioactive nuclides by primary ions with energies down

to zero [15]. Discrepancy between FLUKA and SHIELD was less than 8% at higher beam energies, but 25% at 200 MeV/u ^{238}U ions [4]. This is why it is motivating to revise the simulations with the new version of FLUKA (FLUKA2011) that calculates the nucleus-nucleus interactions below 100 MeV/u.

Monte Carlo simulations by FLUKA2011

It was necessary to use the same settings and physical models as used before to study differences between the two versions of FLUKA. The evaporation model with heavy-fragment evaporation was used. Emission of the high-energy light fragments through the coalescence mechanism was activated. The heavy-ion transport with nuclear interactions was switched on. Low-energy neutron transport was simulated down to thermal energies (10^{-5} eV) and residual nuclei from low-energy neutron interactions were scored [4]. The simulations were performed with the same projectile species. The range of the beam energies was expanded to 25 MeV/u – 1 GeV/u. In this paper, we concentrate on the results for a bulky target made of copper.

Tolerable beam losses

Tolerable beam losses have been defined at the 7th ICFA Workshop on High-intensity Brightness Hadron Beams [3] for uncontrolled proton-beam losses at energies above 100 MeV. To allow hands-on maintenance of accelerator components without unreasonable constraints after 100 days of using the machine, dose-rate levels should be below 1 mSv/h (measured 30 cm from the component surface). This corresponds to the beam losses of about 1 W/m along the beam enclosure [3]. The main goal of our study is to scale the proton beam-loss criterion to heavy-ion machines.

First, a list of nuclides with the biggest contribution to the total activity has been created for each simulation. Examples of graphical representation of the partial relative activities 1 day after the end of irradiation are shown in Figures 2 through 6. Figure 2 reproduces the previous data obtained with FLUKA2008 [4], whereas Figures 3 through 6 show the recent data obtained with FLUKA2011. The partial relative activities are almost the same for all nuclides independently from the projectile mass at energies from 1 GeV/u down to 150 MeV/u. This suggests that radioactive nuclides are produced mostly by secondary particles.

However, the partial relative activities are no longer identical at energies below 150 MeV/u (see Figure 6). There are nuclides produced by some projectile species that are not produced by other projectile species at all. Different nuclide composition must have an influence on the decay-curve of the total residual activity.

Important comparison is between Figure 2 and Figure 3 representing the results from two different versions of FLUKA. The nuclide inventory shows the same list of nuclides produced in the bulky target. However, FLUKA2011 gives smaller partial relative activities for the most dominating nuclides than FLUKA2008. For example, there is a difference of 5% in the case of ^{64}Cu .

Figure 2. Partial relative activities induced in copper bulky target one day after the end of irradiation by different projectiles at 1 GeV/u obtained by FLUKA2008 [4]

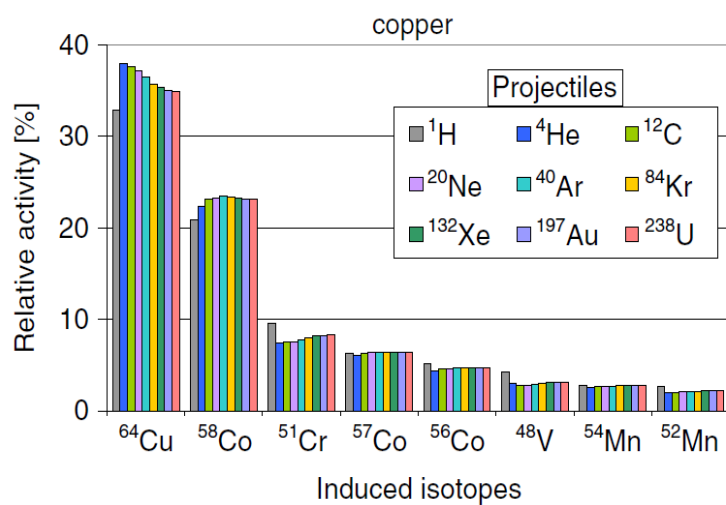


Figure 3. Partial relative activities induced in copper bulky targets one day after the end of irradiation by different projectiles at 1 GeV/u obtained by FLUKA2011

Figure 4. Partial relative activities induced in copper bulky targets one day after the end of irradiation by different projectiles at 500 MeV/u obtained by FLUKA2011

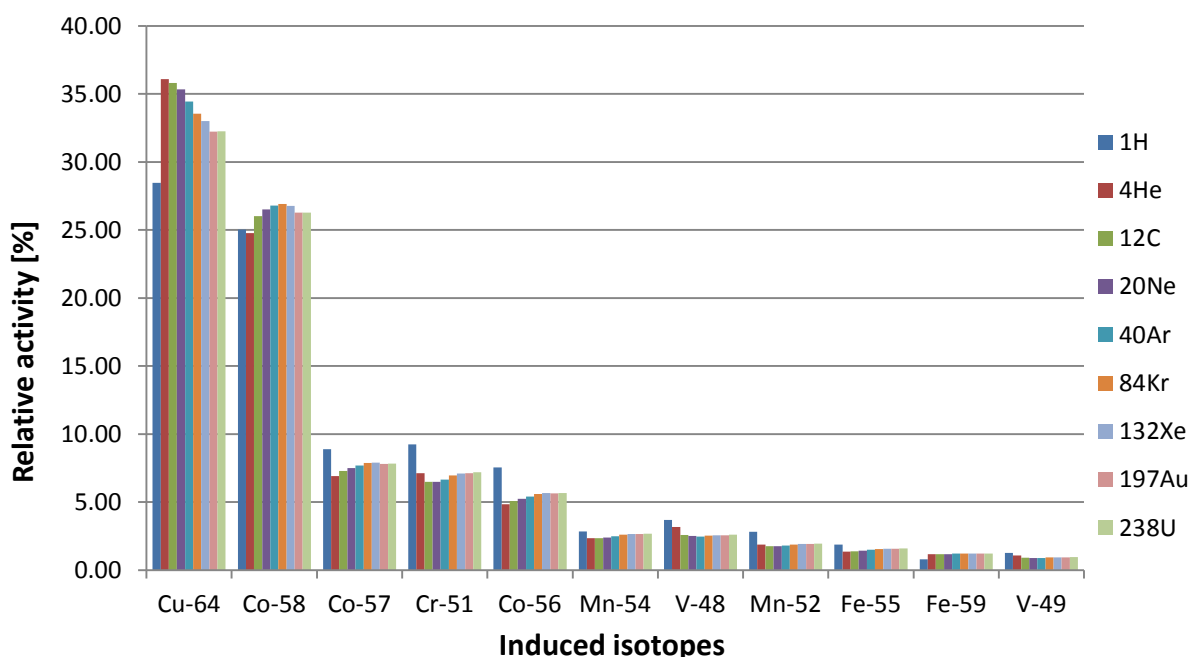


Figure 5. Partial relative activities induced in copper bulky targets one day after the end of irradiation by different projectiles at 150 MeV/u obtained by FLUKA2011

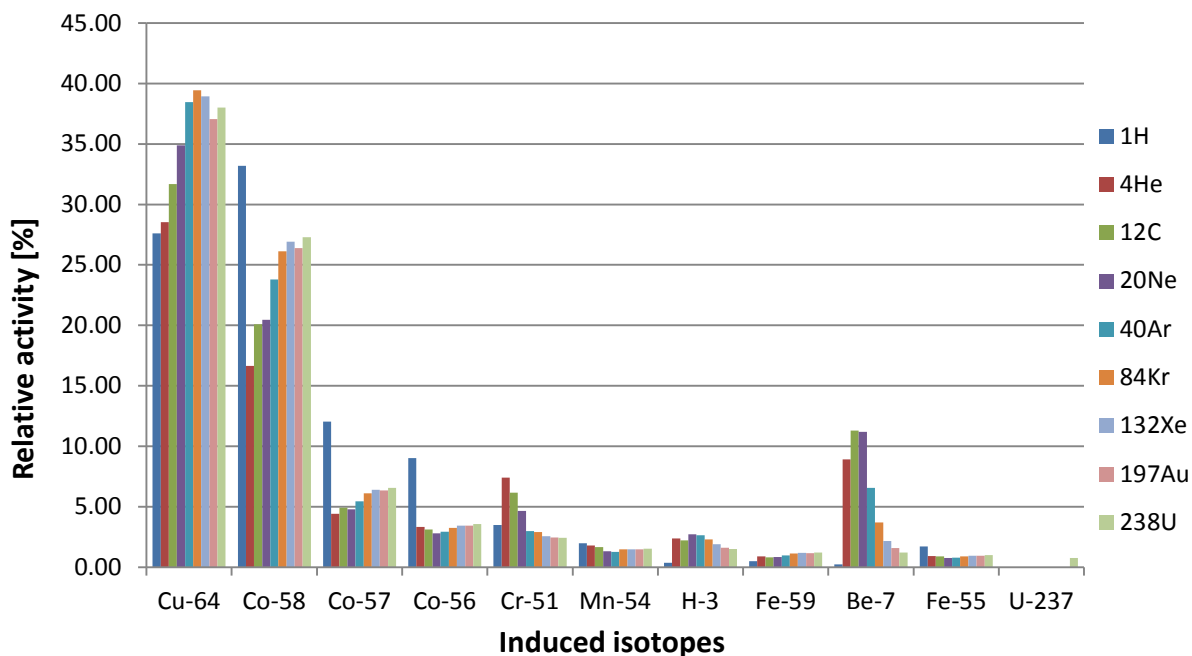
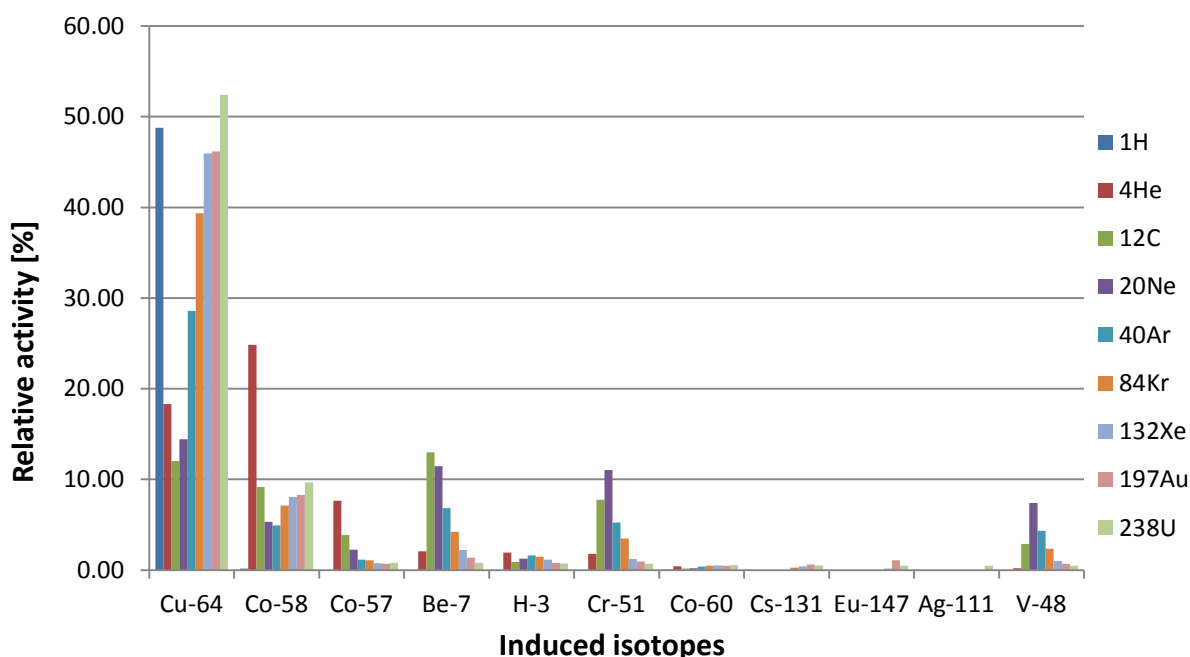


Figure 6. Partial relative activities induced in copper bulky targets one day after the end of irradiation by different projectiles at 25 MeV/u obtained by FLUKA2011



Time evolution of the induced activity

Time evolution of the induced activity is important for establishing a scaling law between the proton and heavy-ion beam-loss criteria. Figures 7 through 10 show the time evolution of the induced activity, A_i , normalised by the activity at the end of irradiation, A_{eoi} . If there is no big difference in the time evolution of the activities induced by different beams (which is a matter of the nuclide composition), a generic curve can be created by averaging the individual curves. The generic curve is representing the time evolution of the induced activity independently from the primary beam particles. It can be subdivided into two parts: (1) an increase of the activity during permanent irradiation = activation part, (2) a decrease of the activity after the end of irradiation = decay part.

Similarly to the nuclide inventory, there are no significant differences in the time evolution of the induced activity for beam energies from 1 GeV/u to 150 MeV/u. However, this is no longer true for energies below 150 MeV/u. Individual curves start deviating from each other shortly after the start of irradiation as well as after the end of irradiation. They do not follow the generic curve, either (see Figure 10). It seems that a reliable universal scaling law cannot be found for energies below 150 MeV/u.

Figure 7. Time evolution of the induced activity in copper bulky target irradiated by different projectiles at 1 GeV/u (GC – the generic curve)

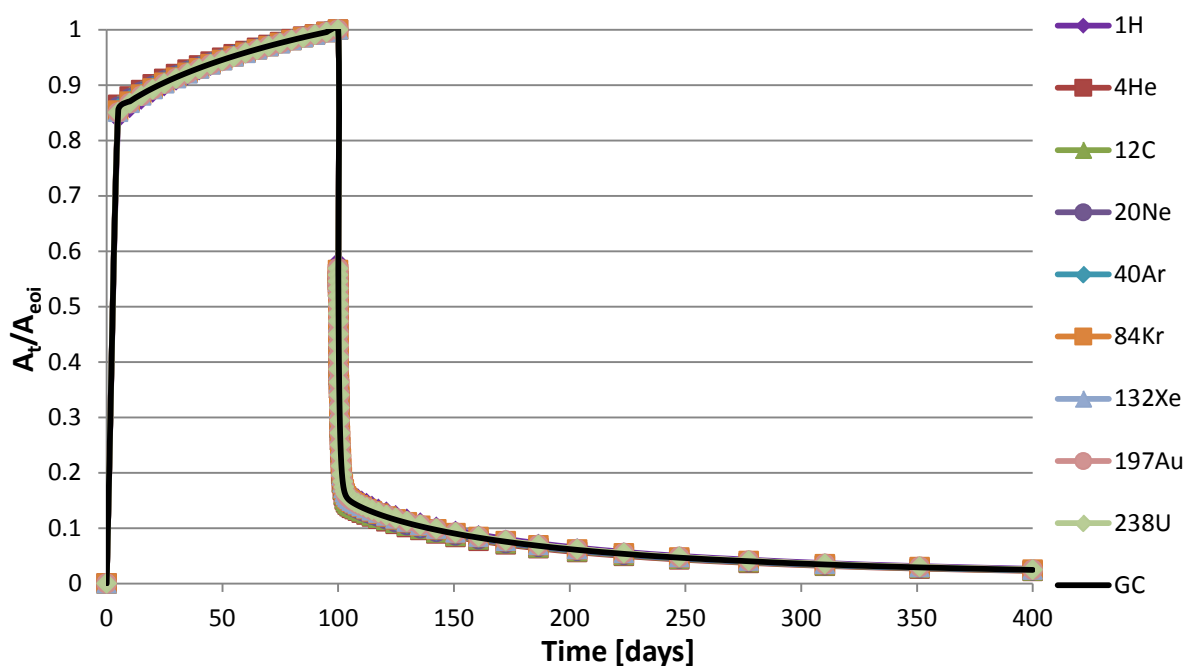


Figure 8. Time evolution of the induced activity in copper bulky target irradiated by different projectiles at 500 MeV/u (GC – the generic curve)

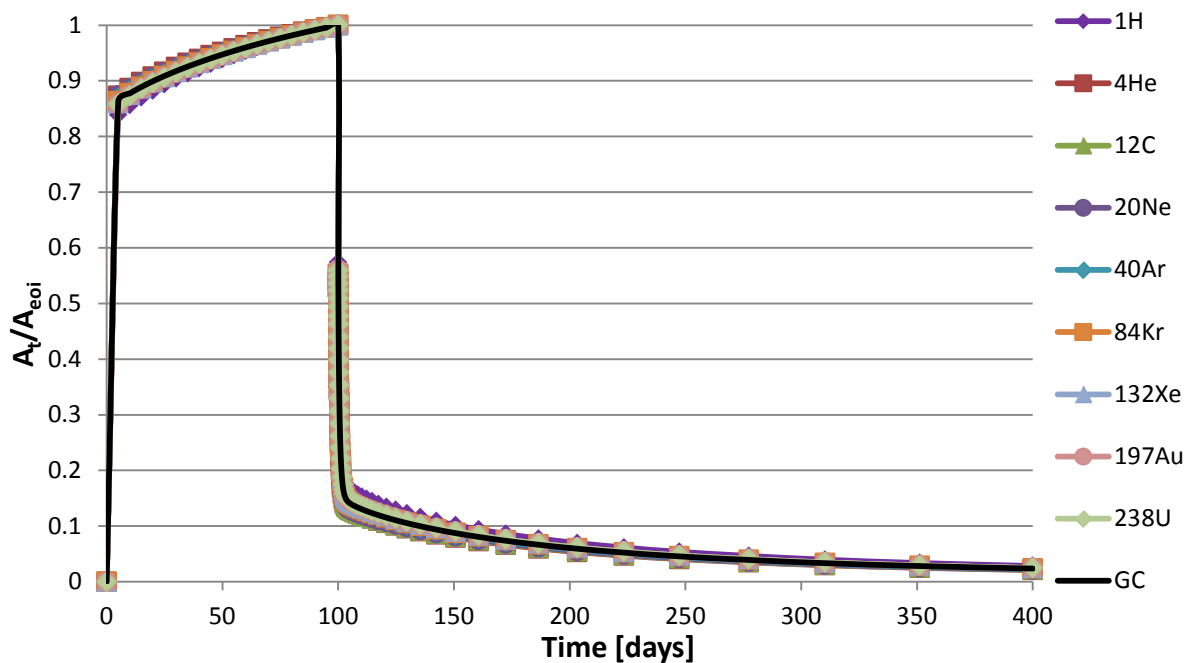


Figure 9. Time evolution of the induced activity in copper bulky target irradiated by different projectiles at 150 MeV/u (GC – the generic curve)

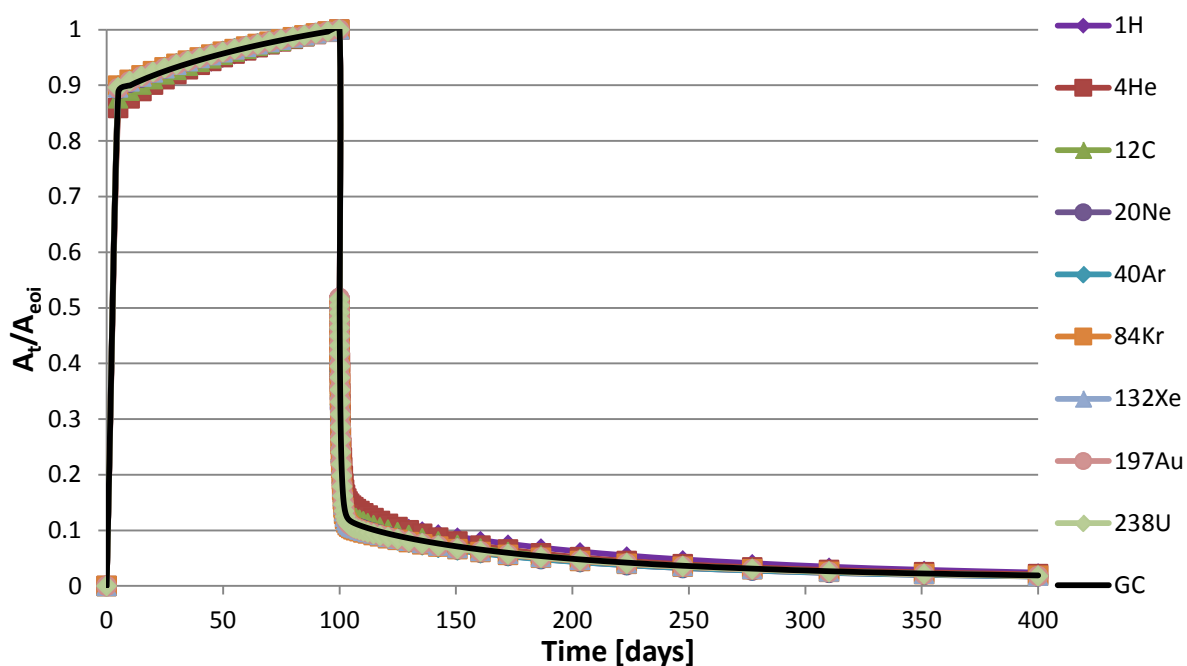
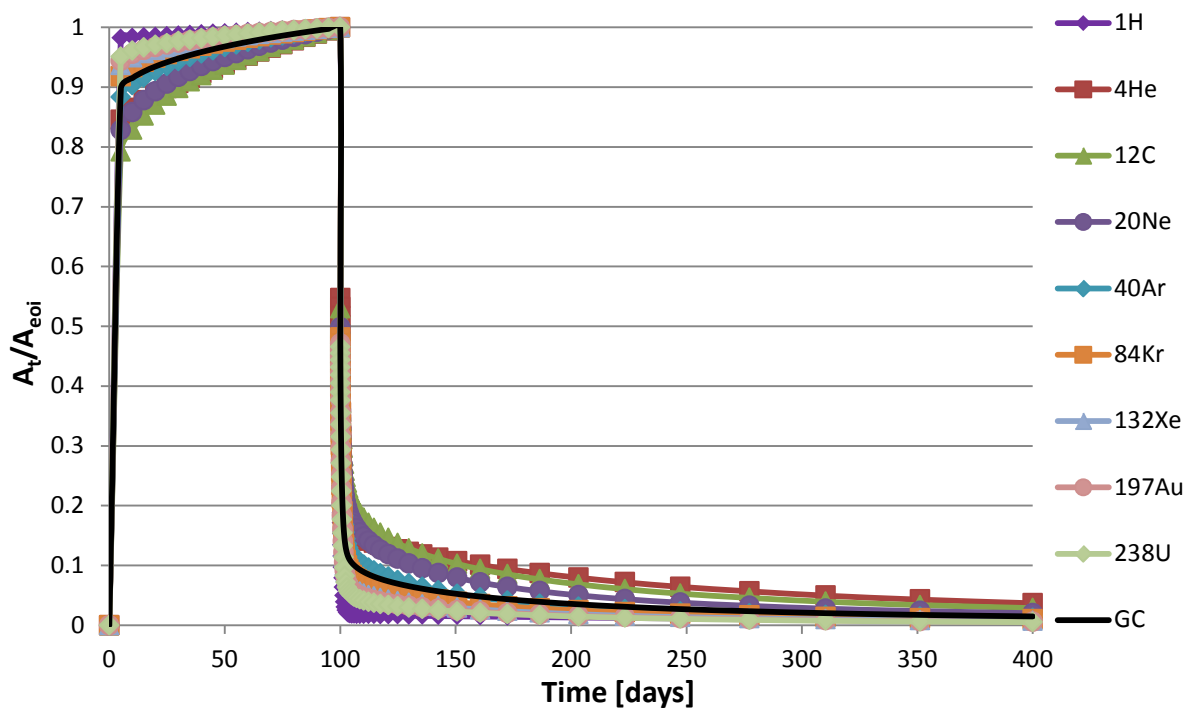


Figure 10. Time evolution of the induced activity in copper bulky target irradiated by different projectiles at 25 MeV/u (GC – the generic curve)



The scaling law for beam-loss tolerance

The previous studies revealed the following: (1) the induced-nuclide inventory does not strongly depend on the projectile species, (2) time evolution of the induced activity correlates to a generic curve, and (3) the total activity induced by 1 W/m of beam losses (the normalised activity) decreases with increasing ion mass and decreasing energy. The scaling factor can therefore be expressed as the ratio of the normalised activity induced by 1 GeV protons, $A_p(1 \text{ GeV})$, to the normalised activity induced by the particles of interest at given energy, $A_i(E)$.

Our recent study verified the previous findings for the copper bulky target irradiated by heavy-ion beams with energies above 150 MeV/u. For comparison, Figure 11 reproduces the data from the previous studies based on FLUKA2008 [4], whereas Figure 12 shows new data based on FLUKA2011. The lower threshold for the nucleus-nucleus interactions in FLUKA2011 leads to higher induced activities due to the increased contribution from projectile fragments. As a consequence, the tolerable beam losses derived from FLUKA2011 are lower compared with the losses derived from FLUKA2008. As an example, they are 40 W/m for uranium beam at 200 MeV/u according to FLUKA2011 instead of, 60 W/m according to FLUKA2008. Tolerable beam losses based on the FLUKA2011 simulations are collected in Table 1.

The situation becomes more complicated at energies below 150 MeV/u. In this case, the activation is driven by the target – as well as the projectile fragments. The contribution from the projectile fragments depends also on the primary beam parameters. Different nuclide composition leads also to different time evolution of the induced activity, which does not comply with a generic curve. A reliable universal scaling law is no longer possible.

Figure 11. Scaling factor for the tolerable beam losses as a function of ion mass – FLUKA2008

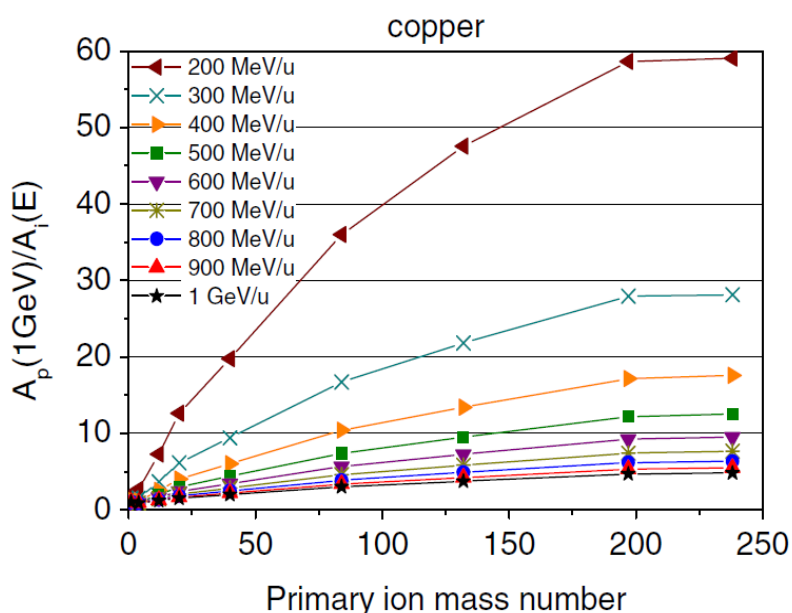


Figure 12. Scaling factor for the tolerable beam losses as a function of ion mass – FLUKA2011

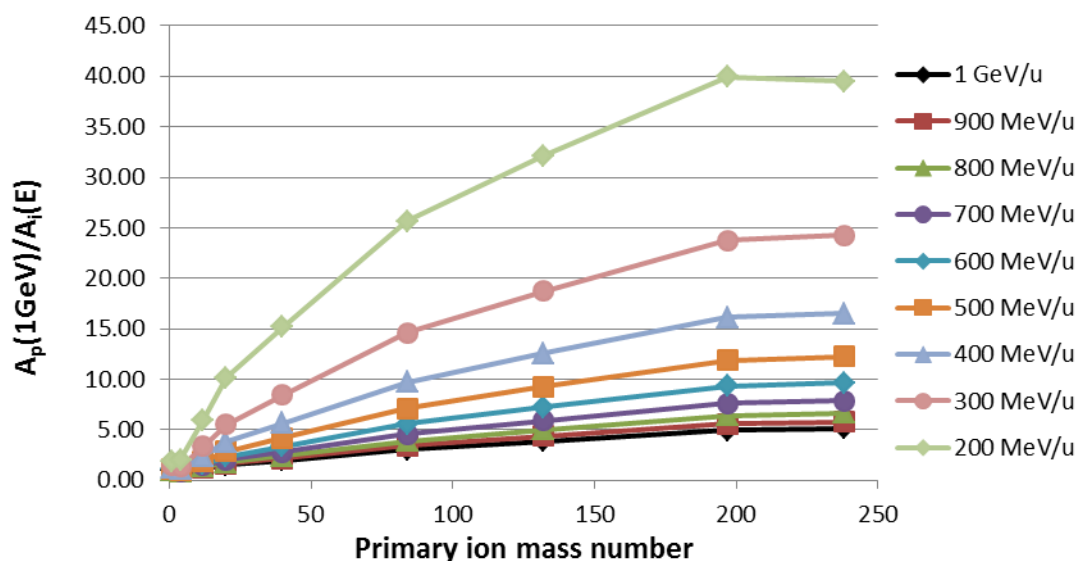


Table 1. Tolerable beam losses according to FLUKA2011

Energy Ion [MeV/u]	Tolerable beam losses for different ion beams at different energies, [W/m]												
	1000	900	800	700	600	500	400	300	200	150	100	50	25
¹ H	1.00	1.01	1.02	1.05	1.09	1.16	1.28	1.49	1.90	2.25	2.84	4.47	8.54
⁴ He	0.87	0.87	0.87	0.88	0.91	0.97	1.09	1.33	1.98	2.85	4.64	9.34	49.86
¹² C	1.18	1.23	1.30	1.42	1.59	1.88	2.37	3.35	5.96	9.76	17.12	35.28	74.36
²⁰ Ne	1.51	1.61	1.77	2.00	2.34	2.86	3.77	5.54	10.15	16.39	28.33	60.41	138.25
⁴⁰ Ar	1.97	2.17	2.42	2.79	3.34	4.19	5.63	8.42	15.17	23.08	37.29	76.62	194.25
⁸⁴ Kr	3.03	3.39	3.88	4.58	5.57	7.10	9.69	14.60	25.67	36.69	54.69	107.10	254.56
¹³² Xe	3.85	4.34	4.99	5.89	7.23	9.24	12.59	18.71	32.10	43.74	62.94	116.75	261.93
¹⁹⁷ Au	4.92	5.56	6.41	7.58	9.29	11.88	16.15	23.75	39.92	52.88	73.26	124.72	262.74
²³⁸ U	5.12	5.77	6.63	7.84	9.61	12.21	16.50	24.25	39.49	51.59	70.07	113.18	245.72

The strikethrough values correspond to the primary beam energies where the scaling law is not reliable.

Conclusion

Generally, our results confirmed that the energy-threshold for nucleus-nucleus interactions does have an influence on activities calculated by FLUKA. At high beam energies (above 150 MeV/u), the scaling law can be applied, but the simulations based on FLUKA2011 lead to lower tolerable beam losses compared to FLUKA2008. For example, they are 40 W/m for uranium beam at 200 MeV/u according to FLUKA2011 instead of

60 W/m according to FLUKA2008. At energies below 150 MeV/u, the energy-threshold for nucleus-nucleus interactions becomes even more important, because the contribution from the projectile fragments to the total induced activity increases. Since this contribution depends on projectile species (mass), the universal scaling law cannot be applied or – at least – becomes less reliable and must be checked/refined by simulating the corresponding dose-rates induced by low-energy beams.

Acknowledgements

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References

- [1] A. H. Sullivan (1992), “A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators”, *Nuclear Technology Publishing*, Chap. 4, pp. 93.
- [2] L. Ulrici et al. (2006), “Radionuclide characterization studies of radioactive waste produced at high-energy accelerators”, *Nucl. Instrum. Methods Phys. Res., Sect A* 562, pp. 596-600.
- [3] N.V. Mokhov, W. Chou (2000) “Proceedings of the 7th ICFA Mini-Workshop on High Brightness Hadron Beams”, *Fermi National Accelerator Laboratory*, pp. 51-61.
- [4] I. Strašík et al. (2010), “Residual activity induced by heavy ions and beam-loss criteria for heavy-ion accelerators”, *Phys. Rev. ST Accel. Beams* 13, 071004, pp. 1-10.
- [5] E. Mustafin et al. (2003), “Influence of electronic stopping power on the total neutron yield of energetic heavy ions”, *Nucl. Instrum. Methods Phys. Res., Sect. A* 501, pp. 553-558.
- [6] I. Strašík et al. (2009), “Simulation of the residual activity induced by high-energy heavy ions”, *Nuclear Technology* 168, p. 643.
- [7] I. Strašík et al. (2008), “Residual activity induced by high-energy heavy ions in stainless steel and copper”, *Proceedings of EPAC08, Genoa, Italy*, pp. 3551-3553.
- [8] P. Spiller et al. (2013), “Status of the SIS100 heavy ion synchrotron project at FAIR”, *Proceedings of the 4th International Particle Accelerator Conference IPAC’13, Shanghai, China*.
- [9] G. Battistoniet et al. (2007), “Proceedings of the Hadronic Shower Simulation Workshop 2006”, *Fermilab, Illinois*, pp. 31.
- [10] A. Fasso et al. (2005), Reports No. CERN-2005-10, No. INFN/TC_05/11, No. SLAC-R-773.
- [11] V.Chetvertkova et al. (2011), “Activation of aluminum by argon: Experimental data and simulations”, *Nuclear Instruments and Methods in Physics Research B* 269, pp. 1336.
- [12] I. Strašík et al. (2010), “Experimental study and simulation of the residual activity induced by high-energy argon ions in copper”, *Nuclear Instruments and Methods in Physics Research B* 268, pp. 573.
- [13] E. Mustafin et al. (2009), “Ion irradiation studies of construction materials for high-power accelerators”, *Radiation Effects & Defects in Solids* 164, pp. 460.
- [14] A. Fertman et al. (2007), “First results of an experimental study of the residual activity induced by high-energy uranium ions in steel and copper”, *Nuclear Instruments and Methods in Physics Research B* 260, pp. 579.
- [15] A.V.Dementyev, N.M. Sobolevsky (1999), “SHIELD – universal Monte Carlo hadron transport code: scope and applications”, *Radiation Measurements* 30, pp. 553-557.