RESIDUAL ACTIVITY IN HEAVY-ION ACCELERATORS AS BEAM-LOSS LIMITING FACTOR

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Abstract

Residual activity is one of the main beam-loss limiting factor in high-energy proton accelerators. In order to ensure 'hands-on' maintenance 4 h after the shutdown, the losses of proton beam should be kept below 1 W/m. It has been shown in our previous publications that the beam-loss criteria for heavy-ion machines may be established by rescaling the '1 W/m criterion' for protons into a similar 'n W/m' criteria for different heavy ions. For protons the scaling factor is obviously 1. Scaling factors for other ions depend on the charge number of the ion and on the beam energy. For example, for U ions with energy E = 200 MeV/u the scaling factor is 60, i.e. 60 W/m losses of U beam are tolerable from the 'hands-on' maintenance point of view, whereas for U ions with E=1 GeV/u the scaling factor is just 5. In the present paper we show that this scaling factor concept has natural limits of applicability. In the case of very low beam energies or in the case of long-term accumulation of the residual activity, the tolerable beam-loss criteria cannot be obtained by simple rescaling of the '1 W/m criterion' with one single number.

INTRODUCTION

An energetic heavy ion penetrating into a bulky target typically destroys several target nuclei. Therefore the total residual activity of the target is usually dominated by the radioactive fragments of the target nuclei and has negligible contribution from the projectile fragments. As it was shown in [1] the relative number of produced radioisotopes in this case does not depend on the type of bombarding heavy ion projectile at the energy range from 200 AMeV to 1 AGeV, and the evolution of the induced radioactivity has the same time dependence for protons and all heavy ion beams. This allows rescaling the whole radioactivity evolution curve from proton induced activity to any heavy ion beam induced activity just by one number. For example, this number is 1/60 in the case of rescaling the 1-GeV-proton induced activity into the activity induced by 200 MeV/u U beam [1]. This means that the well known 1 W/m tolerable beam loss limit for proton accelerators can be rescaled to 60 W/m tolerable loss limit for a 200 MeV/u U beam machine.

This rescaling concept works only for the case when the number of created target fragments considerably exceeds the number of projectile fragments stopped in the bulky target. One could expect a violation of this concept for example in the case of low-energy heavy ion machines. Indeed, low energy heavy ions have very short ranges in a bulky target and do not develop any considerable shower of projectile fragments. Therefore, the interactions with primary projectiles play more important role compared to the production of isotopes via the secondary particles.

The other limit of the simple rescaling concept to be checked is the accumulation of the long-lived isotopes: the long-lived isotope inventory may be different than the short-lived isotope inventory studied in [1].

COMPARISON OF TOTAL ACTIVITIES INDUCED BY PROTON AND URANIUM BEAMS

To study the extremes, let's compare the total activity induced by 1 W beams of protons and U ions lost into a bulky target (a cylinder 20 cm in diameter and 60 cm long, like in [1]) made of Cu.

In order to study the long-term accumulation of isotopes and their following decay, the irradiation time and the consecutive 'cooling-down' time were chosen to be 20 years each. All calculation of the activity were done using FLUKA code [2].

As it is shown in Table 1 the evolution of the total activity has the same time dependence for both p and U beams in the case of high energy beams E=500 and 1000 MeV/u. Indeed, the ratio of the normalised activities (shown in the columns denoted as U/p in Table 1) is within about 30% spread. The normalisation of the activity is done to the end of irradiation (i.e. to the activity at time point 20 years).

Table 1: Time evolution of the total activity for 500 and 1000 MeV/u p and U beams

year	Activity, Bq, 500 MeV/u			Activity, Bq, 1 GeV/u		
	p	U	U/p	p	U	U/p
1	8.2E+9	7.2E+8	0.99	9.3E+9	1.8E+9	0.97
2	8.7E+9	7.6E+8	0.99	9.9E+9	1.9E+9	0.96
5	9.2E+9	8.1E+8	0.99	11E+9	2.0E+9	0.91
10	9.8E+9	8.7E+8	1.00	11E+9	2.2E+9	1.00
20	9.9E+9	8.8E+8	1.00	11E+9	2.2E+9	1.00
21	1.7E+9	1.5E+8	0.99	2.1E+9	3.9E+8	0.93
22	1.2E+9	1.2E+8	1.13	1.6E+9	3.0E+8	0.94
25	7.5E+8	7.6E+7	1.14	1.1E+9	1.9E+8	0.86
30	4.7E+8	4.8E+7	1.15	7.0E+8	1.3E+8	0.93
40	2.6E+8	2.7E+7	1.17	3.9E+8	7.4E+7	0.95

The same shape of the time evolution of the activities for both p and U beams indicates in the case of high-energy beams that the total activity is dominated by the same isotopes, i.e. by the isotopes produced from the target nuclei by the secondary projectiles.

The time evolution of the total activity has a different behaviour in the case of low energy p and U beams. As it is shown in Table 2 only the accumulation of the activity

ISBN 978-3-95450-125-0

during the irradiation (i.e. up to the time point 20 years) is the same for both beams (within a spread of 5%). The time evolution of the activity during 'cooling-down' is very different. Indeed, the ratio of the normalised activities U/p may be a factor of 4 in the case of 100 MeV/u beams and as big as a factor of 9 in the case of 50 MeV/u beams. In order to understand this difference let's analyse the isotope inventory more closely.

Table 2: Time evolution of the total activity for 50 and 100 MeV/u p and U beams

year	Activity, Bq, 50 MeV/u			Activity, Bq, 100 MeV/u		
	p	U	U/p	p	U	U/p
1	2.1E+9	7.0E+7	0.97	3.1E+9	1.3E+8	0.98
2	2.1E+9	7.2E+7	0.90	3.3E+9	1.3E+8	0.92
5	2.2E+9	7.4E+7	0.95	3.4E+9	1.4E+8	0.96
10	2.2E+9	7.8E+7	1.00	3.5E+9	1.5E+8	1.00
20	2.2E+9	7.9E+7	1.00	3.5E+9	1.5E+8	1.00
21	8.3E+7	8.6E+6	3.00	3.4E+8	2.6E+7	1.78
22	4.8E+7	7.6E+6	4.58	2.2E+8	2.2E+7	2.33
25	2.3E+7	6.0E+6	7.15	1.2E+8	1.7E+7	3.31
30	1.4E+7	4.4E+6	9.20	7.4E+7	1.2E+7	3.78
40	8.2E+6	2.7E+6	8.94	4.0E+7	7.2E+6	4.20

The isotopes contributing into the total activity at the time point 40 years is presented for 50 and 1000 MeV/u p and U beams in Table 3 and Table 4. The half-lives of the isotopes are presented in column denote as $T_{1/2}$ and given in years. The activities of the isotopes are presented in the column denoted Activity and given in Bq.

Table 3: Dominating isotopes contributing to the total activity of Cu target irradiated by 50 and 1000 MeV/u beams of U ions

50 MeV/u			1000 MeV/u		
Element	$\mathbf{T_{1/2}}$	**Activity**	**Element**	$\mathbf{T_{1/2}}$	**Activity**
H-3	12.33	1.72E+6	H-3	12.33	4.39E+7
Ni-63	100.11	7.51E+5	Ni-63	100.11	2.05E+7
Co-60	5.27	1.29E+5	Co-60	5.27	4.39E+6
Ba-133	10.5	9.25E+3	Fe-55	2.73	5.66E+5
Ar-42	32.9	5.91E+3	Ti-44	64.81	2.87E+5
Gd-148	74.6	5.28E+3	Sc-44	0.0004	2.23E+5
Pm-145	10.7	4.79E+3	Ar-39	268.99	1.59E+5
K-42	0.0014	4.66E+3	Ar-42	32.91	2.96E+4
Tb-157	71.0	3.27E+3	Ni-59	80004	2.68E+4
Si-32	28.8	2.99E+3	Si-32	132	2.43E+4
Sr-90	28.8	2.48E+3	K-42	0.00	2.33E+4
Ar-39	269.0	2.33E+3	Bi-207	31.55	1.98E+4
P-32	0.04	2.27E+3	P-32	0.04	1.85E+4
Y-90	0.0073	1.97E+3	Pb-210	22.30	1.79E+4

One may notice that the contribution of heavy fragments of U ions is very minor and therefore cannot influence the time evolution of the total activity.

The main contribution comes from the fragments of the target nuclei, namely from H-3 and Ni-63. The ratio of the activity of H-3 to the activity of Ni-63 is about the same (about a factor of 25) in the case of U beam of E=1000 MeV/u, p beam of E=1000 MeV and U beam of E=50 MeV/u. But in the case of p beam of energy 50 MeV the isotope Ni-63 is dominating over the isotope H-3 by a factor of 4. These isotopes have different half-lives and this makes the difference in the time evolution of the total activity.

Table 4: Dominating isotopes contributing to the total activity of Cu target irradiated by 50 and 1000 MeV protons

50 MeV			1000 MeV		
Element	$\mathbf{T_{1/2}}$	**Activity**	**Element**	$\mathbf{T_{1/2}}$	**Activity**
Ni-63	100.11	5.69E+6	H-3	12.33	2.85E+8
H-3	12.33	1.26E+6	Ni-63	100.11	1.11E+8
Co-60	5.27	1.13E+6	Co-60	5.27	2.07E+7
Fe-55	2.73	9.94E+4	Ti-44	64.81	4.64E+6
Ni-59	80004	4.09E+4	Sc-44	0.0004	3.60E+6
Co-57	0.7445	4.82E-1	Fe-55	2.73	3.09E+6
Mn-54	0.8555	9.10E-2	Ar-39	267	2.38E+6
Zn-65	0.6691	5.32E-2	Ni-59	80004	1.32E+5
Co-58	0.1940	1.3E-23	Ca-41	102993	8.40E+3
Co-56	0.2117	9.0E-24	Cl-36	300989	2.30E+3

CONCLUSION

The rescaling concept of [1] works well for the activity with the domination of the short-lived isotopes even for low energies of the ion beams and but it fails in the case of accumulation of long-lived isotopes. The reason for the violation of the concept is not the contribution of the heavy fragments created from the heavy ion projectiles. The main reason is the difference in the production rates of major contributing isotopes H-3 and Ni-63 from the interaction of protons with the target Cu nuclei at different energies.

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ISBN 978-3-95450-125-0