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UNCONTROLLED BEAM LOSS ESTIMATED LIMITS ON PROTON AND URANIUM ION BEAMS FOR ALLOWING HANDS-ON MAINTENANCE IN THE RARE ISOTOPE ACCELERATOR LINAC

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ABSTRACT

Limits on uncontrolled beam particle losses are estimated for proton and uranium ion beams when accelerated by the Rare Isotope Accelerator linac. The estimated losses are limited by a hands–on maintenance dose rate limit of 100 mrem per hour at 30 cm after 4 hours. The allowed beam loss per meter as a function of ion energy, for the dose rate at the maintenance limit, is presented in terms of the allowed absolute number of particles lost per second and the allowed percentage loss of total beam. Results are given for a 400 kW beam of protons and for a 400 kW beam of uranium ions. Methods and supporting experimental information are discussed.

I. INTRODUCTION

Radiation doses to personnel at accelerators are obtained predominately while performing maintenance activities. The radiation responsible for these doses is induced generally by beam losses during operations. Beam losses may be classified as either Controlled (*e.g.* at collimators, scrapers, dumps, and stripping regions) or Uncontrolled (*e.g.* from gas stripping and beam halo). Controlled losses are better understood and local shielding and remoted handling techniques can be designed to minimize doses. Uncontrolled losses are not as well understood because the amount and locations are difficult to know *pre hoc.*

For efficient and cost-effective accelerator operations, it is highly desired to allow hands-on maintenance for as much of the accelerator as possible. Dose rate criteria must be established and beam losses must be understood early on in accelerator design, to allow decisions on if and where hands-on maintenance can be reasonably achieved. It is therefore desired to estimate dose rates from unconrolled losses so that accelerator designs may be optimized to minimize them.

II. DOSE RATE CRITERION

Operating experience[1] at LAMPF and the PSR, and design studies for the Accelerator Production of Tritium (APT) project, all at Los Alamos National Laboratory, and the Spallation Neutron Source at Oak Ridge National Laboratory determined that the dose rate for hands-on maintenance should not to exceed 100 mrem per hour at one foot (30 cm). This limit is reasonable for several administrative and safety reasons. At dose rates of 100 mrem in an hour or greater, at 30 cm from the source (or through the surface from which it emanates), the area must be classified a "High Radiation Area". There are attending strict requirements on monitoring and access control. When working within High Radiation Areas it is possible to obtain significant fractions of radiation dose limits in short periods. Maximum permissible exposure is 5000 mrem per year, but lower limits will be administratively in place, typically 500 mrem in a year. When working in a High Radiation Area it is possible that administrative limits can be exceeded within one work-shift.

In addition, it is desirable to let very short-lived activities decay before personnel commence work after the accelerator is shut down for maintenance. For example, ^{11}C ($T_{1/2}$ = 20.4 minutes) will be abundantly produced by activation of air in the linac tunnel. Waiting 10 half-lives (4 hours) will be prudent. **Therefore, a dose rate criterion for allowing hands-on maintenance is for rates to be less than 100 mrem in an hour at 30 cm, after 4 hours is reasonable and should be adopted at RIA.**

III. CALCULATIONS AND RESULTS

III.A. JUSTIFICATION OF BEAM SPECIES FOR CALCULATIONS

Proton and ^{3}He ion beams will have the highest energies and intensities at RIA. Table I compares the fast-neutron thick-target yields from these beams and beams of heavy ions stopping in a medium-mass target[2] such as copper.

Table 1
Estimated thick-target high-energy (> 5 MeV) neutron yields for RIA Beams stopping in a medium-mass target (*e.g.* copper).

Beam Ion And Specific Energy	Current (pμA) for ~100 kW	Thick-Target High-Energy Neutrons/ion	Relative to protons
Proton 930 MeV	108	1.6	1.0
3-Helium 730 MeV/u	47	3.5	1.0
Carbon 500 MeV/u	14	5.4	0.44
Neon 500 MeV/u	8.3	3.9	0.04
Niobium 500 MeV/u	1.8	6.9	0.07
Uranium 403 MeV/u	1	20	0.12

The neutron yield values presented in Table 1 from proton and ^{3}He ion interactions are calculated using Monte Carlo codes. For ions heavier than ^{3}He, yields are *estimated,* using results of sytematical studies[3,4,5] of thick target yields from ion beams within RIA's energy regime. In the systematical studies by Kurosawa et al.[3,4], the energy dependence of thick target yields was found to be ~ $(E/A)^2$. A simple prescription was developed to calculate the thick target neutron yield for different combinations of ions, targets and ion energies. The estimates in Table 1 were made using this prescription.

One may test these estimates using other recent data. Recently, measurements of neutron yields were made at GSI[5], using ^{12}C and ^{238}U ions having energies of 1A GeV striking thick Fe targets. For neutron energies $E_n > 25$ MeV, the reported yield is 45 neutrons/ion from carbon ions, and 140 neutrons/ion from uranium ions. Scaling the GSI result to predict the yield from carbon ions at 500A MeV gives about 11 neutrons/ion having $E_n > 25$ MeV. This is about twice the estimated value when given in Table 1. However, one expects that the number of neutrons having $E_n > 5$ MeV should be larger than the number having $E_n > 25$ MeV. Similarly, scaling the GSI result for uranium to predict the yield from uranium ions having 403A MeV gives about 23 neutrons/ion, which is about the same as the value given in Table 1, although, as for carbon, one expects more neutrons when $E_n > 5$ MeV compared to when $E_n > 25$ MeV.

In addition, simple Monte Carlo transport calculations were carried out for 930 MeV proton and 403A MeV ^{238}U beams incident on thick Cu targets (60 cm-thick in both cases). At the same beam power (see Table 1: the ratio of ^{238}U-to-proton particle current is about 1 to 108), secondary neutron production by ^{238}U ions was found to be about 5% of the yield from the proton beam. This can be compared to the result in Table 1, where one divides the estimated number of neutrons produced by uranium at 403A MeV by the calculated number produced by protons at 930 MeV for the same beam power. This result is about 12%.

Part of the difference between the ratio of yields calculated using a Monte Carlo code, and same ratio taken where the yield from uranium was estimated, is attributable to the stopping range for the uranium ions being only about 0.44 cm. The stopping range for protons having 930 MeV is about 49 cm. Therefore, many neutrons from the uranium reactions may be absorbed by thick material encountered by the neutrons in the forward direction, whereas neutrons from proton interactions are produced along the proton's much larger range, hence have a larger possibility to escape. **In general, the estimated heavy ion yields appear to be reliable to within factors of two or so.**

For a first-order and conservative estimate of radiation dose, it appears appropriate to choose activation by the proton beam. Although heavier ions produce more neutrons per interaction, leading to activation and exposure, at a given power the particle current of heavier ions is smaller than that for protons. **Therefore, it is expected that, for equal power, exposures will be smaller for ion beams such as carbon and heavier, when compared to protons.**

III.B. JUSTIFICATION FOR CALCULATION APPROACH

Recently, Titarenko *et al.*[6] measured residual product nuclide production cross sections for 0.2 GeV and 2.6 GeV proton beams, and a 0.2A GeV ^{12}C ion beam, irradiating thin ^{59}Co and natural Cu targets. The product nuclei were identified by off-line gamma spectroscopy.

We used the measured cross sections to calculate inventories after an irradiation time of one year. Exposure rates at 30 cm were then calculated at regular intervals over a "cooling" time of 30 days, using the code MicroShield[7] for those observed nuclides that are contained in the ICRP-38 library. MicroShield can estimate contributions to the exposure rate from decays of parent nuclides, and buildup and decays of daughter nuclides.

Figure 1 shows the calculated exposure rates for a "cooling" time of 30 days after 30-day irradiations by 400 kW beams, based on the cross section measurements by Titarenko *et al.*[1], using the MicroShield code. Effective dose rates in units of rem/hr may be easily estimated from these calculated exposure rates. An exposure of 1 Roentgen leads nearly to a dose of 1 rad. The quality factor relating a dose from photons in units of rads to a dose equivalent in units of rems is unity.

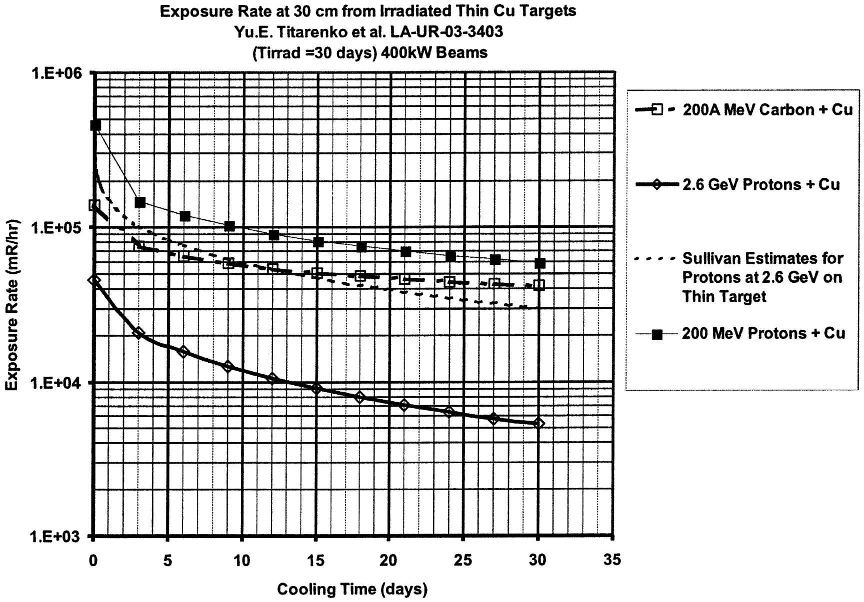

Figure 1: The exposure rates versus cooling time are shown for 400 kW proton and ^{12}C ion beams on thin Cu targets.

Sullivan[8] has derived a semi-empirical equation for the dose-equivalent rate at 1 meter from a "thin" target of a medium-mass material (*e.g.* Cu, Fe) having a known amount of spallation-induced radioactivity produced by a proton beam. This equation is:

$$\boldsymbol{D} = \mathbf{5.2x10^{-17}\,\Phi\,ln}\left[\frac{\boldsymbol{T+t}}{\boldsymbol{t}}\right] \text{ Sv/hr-g at 1 meter.} \qquad (1)$$

Here, T is the irradiation time, and t is the decay (cooling) time after the beam is turned off. Φ is the proton beam flux. This equation is independent of hadron energy above 0.2 GeV, and is valid for "thin" targets, *i.e.* thinner than the interaction length of hadrons producing the spallation reactions[7]. An accelerator beam pipe may be considered a "thin target" to uncontrolled-beam-loss particles.

Exposure rates were calculated for a 400 kW proton beam having 2.6 GeV total energy striking targets having masses given by Titarenko *et al.*[6] The results are shown in Figure 1 and are in reasonable agreement with the estimates made from measurements.

It is then reasonable to assume that Sullivan's semi-emperical formulae may be adopted for first-order estimates of dose rates from uncontrolled losses within the RIA linac, after modifications are made for hadron production when the beam energy is less than 1 GeV.

III.C. CALCULATIONAL METHOD FOR DOSES FROM PROTON BEAM LOSSES

The following analysis is similar to that presented in reference 7. The produced radioactivity and resulting dose originates from spallation products (mainly neutrons when the primary beam energy is below 1 GeV) of interactions between protons lost from the beam and accelerator materials they strike.

Sullivan's semi-empirical formula[7] for the activity produced in spallation reactions between a proton beam and a target of a medium-mass material (*e.g.* Cu, Fe) is:

$$\boldsymbol{S} = \mathbf{0.031\,ln}\left[\frac{\boldsymbol{T+t}}{\boldsymbol{t}}\right] \text{ Bq per spallation interaction per second.} \qquad (2)$$

Here, T is the irradiation time, and t is the decay (cooling) time after the beam is turned off.

The number of secondary neutrons produced from Cu and Fe targets as a function of proton energy when the primary proton beam energy is below 1 GeV can be estimated using analysis by Tesch[9] as presented by Cossairt[10]. At 1 GeV, the number of produced neutrons per proton is about 7. At 100 MeV, the number is about 0.2. Therefore, neutron production and its energy dependence for beam energies below 1 GeV may be approximated by:

$$\boldsymbol{N = 7E^{1.5}} \text{ neutrons per proton, where } E \text{ has units of GeV.} \quad (3)$$

This number should be increased by 50% due to radioactivity produced by low energy and thermal neutrons, which not included in the above expression[7].

Therefore, the activity normalized to lost beam current is given by

$$\boldsymbol{S = 0.33E^{1.5} \ln\left[\frac{T+t}{t}\right]} \text{ Bq per proton per second,} \quad (4)$$

or, in terms of power loss:

$$\boldsymbol{S = 2.06E^{0.5} \ln\left[\frac{T+t}{t}\right]} \text{ GBq per watt.} \quad (5)$$

Assuming personnel are exposed to 10% of the activity providing the dose[7] and using a dose conversion constant[7] of 220 fSv/hr/Bq at 50 cm, the dose rate, *D*, at 50 cm after *T* days of irradiation and *t* days of cooling, is (for 1 W/m loss):

$$\boldsymbol{D = 45.4E^{0.5} \ln\left[\frac{T+t}{t}\right]} \ \mu\text{Sv/hr at 50 cm (per 1 W/m loss)} \quad (6).$$

Expressing the dose rate in rem/hr for current regulatory purposes (1 Sv = 100 rems), the dose rate in rem/hr at 30 cm (about 1 foot) is:

$$\boldsymbol{D = 12.7E^{0.5} p \ln\left[\frac{T+t}{t}\right]} \text{ mrem/hr at 30 cm (per } p \text{ W/m loss)} \quad (7).$$

III.D. RESULTS FOR PROTON BEAM LOSSES

Assuming an irradiation time of 100 days and a cooling time of 4 hours, the graph of dose rate verses beam energy is shown in Fig. 2:

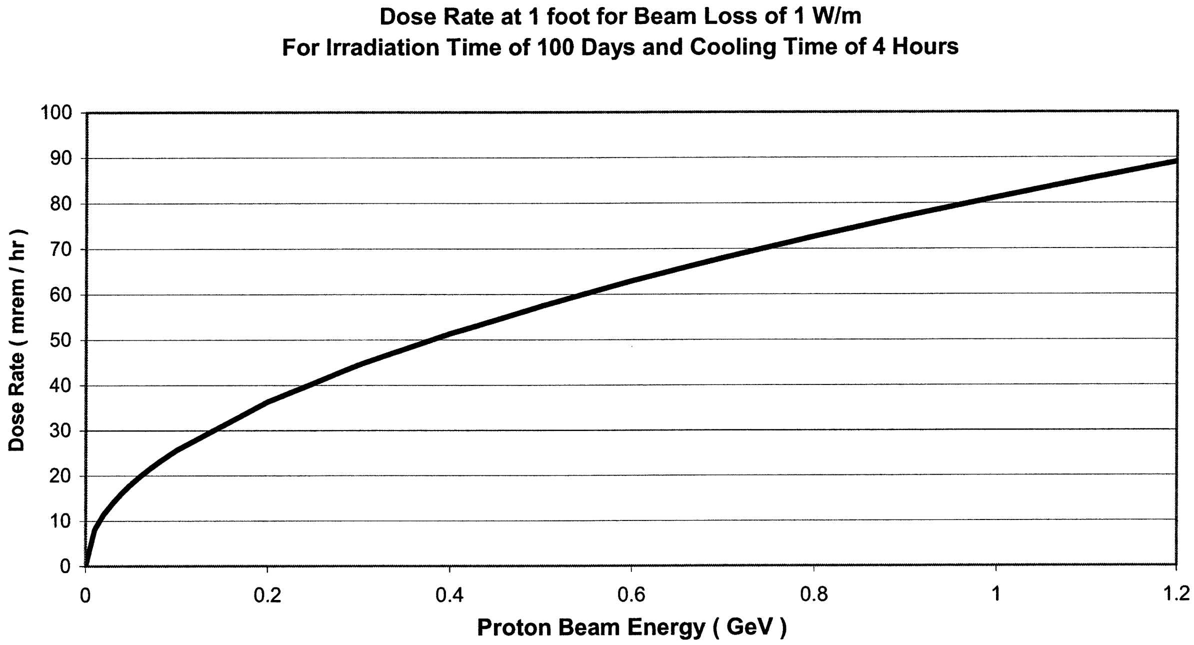

Figure 2: The dose rate at 30 cm estimated for a beam loss of 1 watt per meter is shown as a function of proton beam energy, for an irradiation time of 100 days and a cooling time of 4 hours.

This analysis for protons agrees with that done for the SNS[11].

The power loss in Watts per meter that leads to 100 mrem in an hour at 30 cm is shown as a function of proton beam energy in Fig.3, for the same irradiation and cooling conditions.

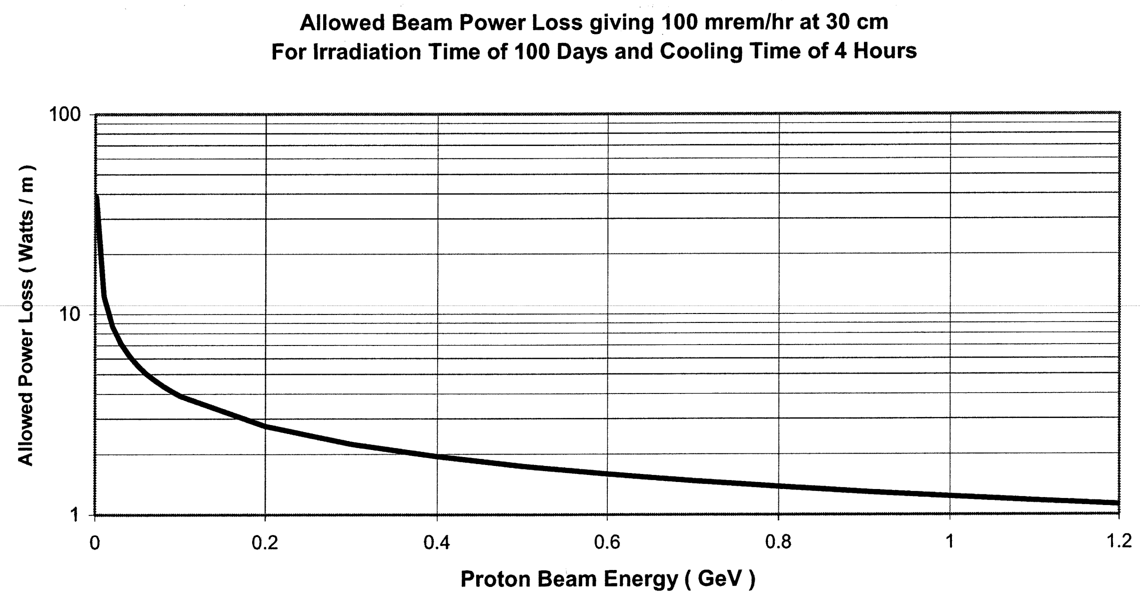

Figure 3: The allowed beam power loss per meter that leads to 100 mrem/hr at 30 cm is shown as a function of proton beam energy, for an irradiation time of 100 days and a cooling time of 4 hours.

This power loss, expressed as the number of particles per second lost per meter and as the fraction of the primary beam lost per meter, is shown in Fig. 4 as a function of proton beam energy.

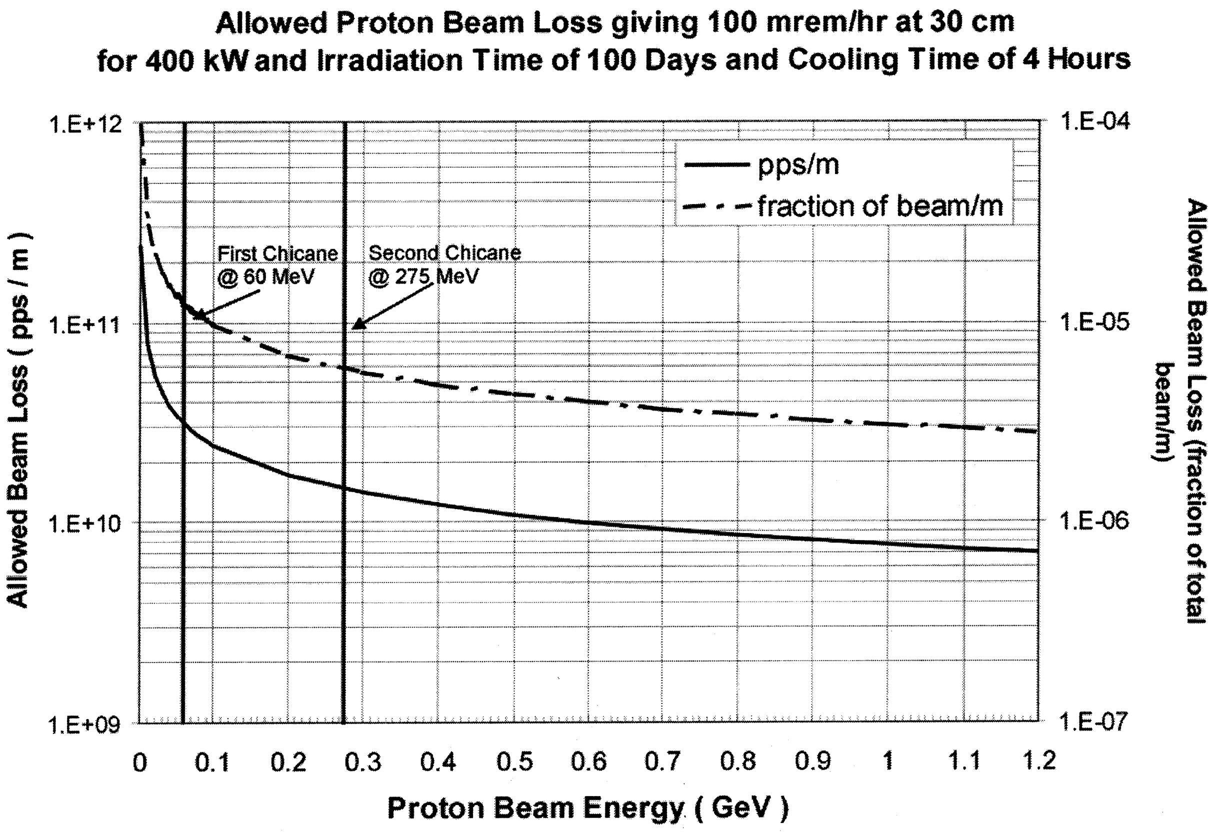

Figure 4: The allowed losses of protons per meter that lead to 100 mrem/hr at 30 cm are shown as a function of proton beam energy (GeV). The losses are expressed as the number of protons per second lost per meter (solid line and left axis) and as the fraction of the primary beam lost per meter (dot-dash line and right axis). A total beam power of 400 kW, an irradiation time of 100 days and a cooling time of 4 hours are assumed. For reference, the proton energies at the first and second stripping region chicanes are also shown, by the labeled solid vertical lines at 60 and 275 MeV.

III.E. CALCULATION AND RESULTS FOR ^{238}U BEAM LOSSES

For ^{238}U ions, we use the experimental measurements of neutrons made at GSI[12] and the energy systematics deduced by Kurosawa et al.[3,4] as discussed in Section III.A. Equation 3 becomes

$$\boldsymbol{N = 140(E / A)^2} \text{ neutrons per proton,} \quad (8)$$

where *E/A* has units of GeV per nucleon. The activity per unit power loss is then

$$\boldsymbol{S = 0.17(E / A)\ln\left[\frac{T+t}{t}\right]} \text{ GBq per watt.} \quad (9)$$

The dose-equivalent rate at 50 cm per 1 W/m beam loss is

$$\boldsymbol{D = 37.4(E / A)\ln\left[\frac{T+t}{t}\right]} \ \mu\text{Sv/hr at 50 cm (per 1 W/m loss).} \quad (10)$$

Finally, the dose-equivalent rate at 30 cm is

$$\boldsymbol{D} = \mathbf{10.4}(\boldsymbol{E}/\boldsymbol{A})\ln\left[\frac{T+t}{t}\right] \text{ mrem/hr at 30 cm (per 1 W/m loss).} \qquad (11)$$

The beam loss, expressed as the number of ions per second lost per meter and as the fractional loss of the primary beam, that gives 100 mrem in an hour at 30 cm is shown in Fig. 5 as a function of uranium beam specific energy.

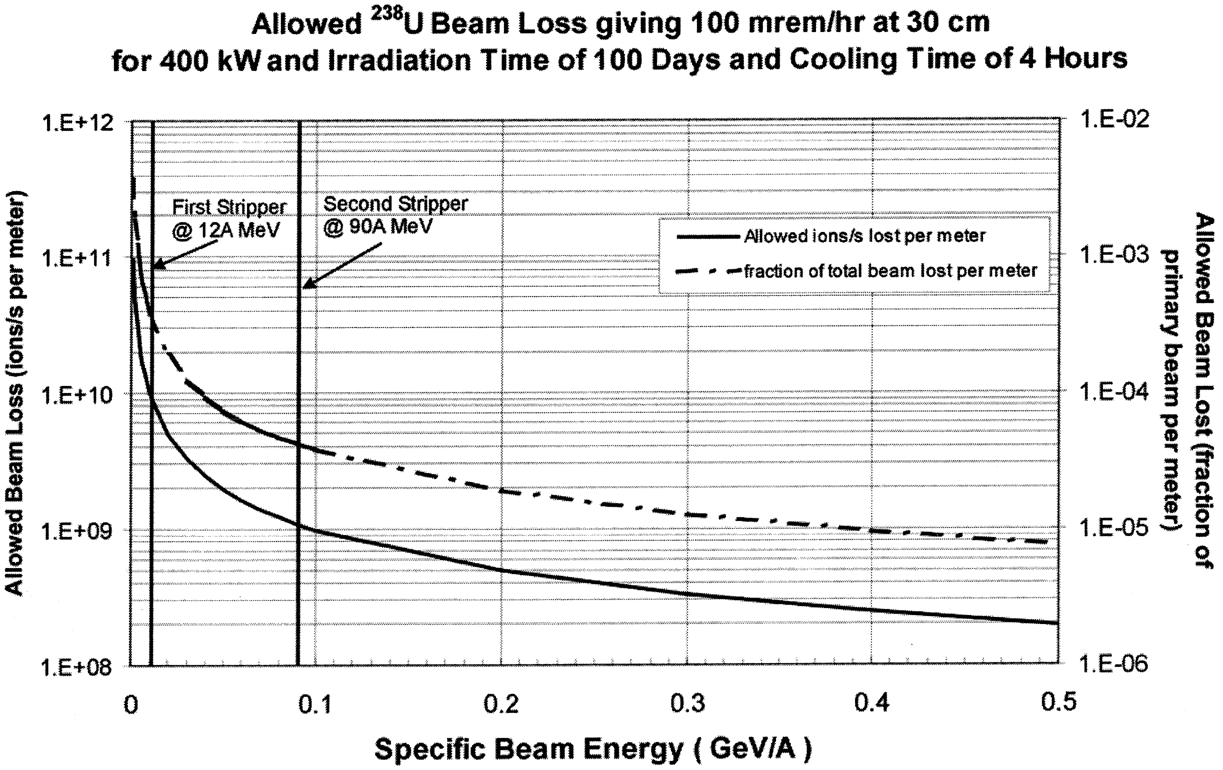

Figure 5: The allowed losses of uranium ions per meter that lead to 100 mrem/hr at 30 cm is shown as a function of ion beam specific energy (GeV per nucleon). The losses are expressed as the number of ions per second lost per meter (solid line and left axis) and as the fraction of the primary beam lost per meter (dot-dash line and right axis). A total beam power of 400 kW, an irradiation time of 100 days and a cooling time of 4 hours are assumed. For reference, the energies of the uranium ions at the first and second stripping region chicanes are also shown, by the labeled solid vertical lines at 12A MeV and 90A MeV.

One may compare the allowed beam loss for protons at maximum energy, given in Fig. 4, to that for uranium ions, given in Fig. 5. **The ratio of allowed particle losses of protons to uranium ions is about 30 at the highest possible beam energies.**

IV. CONCLUSION

Equations 7 and 11 were developed to estimate dose rates from uncontrolled proton and uranium beam losses along the accelerator (beam energy increases with length). The analysis for protons agrees with that done for the SNS[11] and shows hands-on maintenance can be reasonably expected for uncontrolled proton beam losses having up to at least 1.2 GeV beam energy. For 1.2 GeV protons, 1.2 W/m (about 7.0 x 10^9 pps) is allowed. The analysis was extended to uranium ions. For 0.4A GeV ^{238}U ions, 3.8 W/m is allowed (about 2.4 x 10^8 ions per second). These conclusions are based on general considerations and must be verified by detailed transport calculations.

V. ACKNOWLEDGEMENTS

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