BEAM LOSS LIMITS IN HIGH POWER PROTON LINEAR ACCELERATORS

L. Tchelidze, European Spallation Source ESS AB, Lund, Sweden
J. Stovall, Rutherford Appleton Laboratory, Chilton, Oxfordshire, UK

Abstract

High power hadron linear accelerators are designed based on 1 W/m loss limit criteria. The loss limit originates from the hands-on-maintenance allowance of accelerators and limits average dose rate level to less than 0.1 - 1 mSv/h (limited access time) at 30 - 40 cm from a machine after 100 days of continuous operation and 4 hours of down time. However, machine activation and thus beam loss limit depends on incident particle energy and 1 W/m is only a good approximation for energies 100 - 200 MeV and higher (in H-/H+ accelerators). At lower energies though, one could allow much higher than 1 W/m without excess activation. A careful analysis of energy dependent loss limits was performed for proton linear accelerators as part of the study for the European Spallation Source (ESS) linac (linear accelerator), for energy range 5 MeV – 80 MeV. ESS linac is to be built in Lund, Sweden and will deliver 5 MW proton beam to the target. MARS code was used for calculations and beam loss limits were derived as a function of energy.

INTRODUCTION

The ESS linac will accelerate protons up to 2 GeV through a variety of accelerating structures. In the linac, the protons will be bunched and focused by electromagnetic fields to prevent them from striking the walls of the accelerator and being lost. However, any protons that escape these confining fields cannot be recaptured and will eventually interact with the linac parent materials via various processes. The nuclear reactions between the errant protons and the atoms of the parent materials of the accelerator will result in prompt radiation and induced activity. In this report we address only the induced radioactivity resulting from proton beam losses in the RFQ (radiofrequency quadrupole) and DTL (drift tube linac) section of the ESS accelerator. Based on these results we propose beam loss criteria that can be used by accelerator designers that will ensure residual activation levels in the early part of the accelerator, which will be consistent with safe hands-on maintenance as defined by statutory regulations, ESS administrative requirements and best practice in the accelerator community.

DOSE LIMITS

The Swedish law limits the annual effective dose to radiation workers to 20 mSv/y [1]. However, the ESS general safety objective suggests a limit of 10 mSv/y for normal operations [2]. Note that the natural background in southern Sweden is few (1 - 4.5) mSv/y [3].

We differentiate between supervised radiation area and controlled radiation area [4]. For temporary work in a supervised area, no detailed job or dose planning is required. The radiological areas are classified as a function of the dose rates measured at 40 cm from accelerating structure, where it is considered to correspond to the local ambient dose rate. Since we are only concerned with limited term (low occupancy) exposure and to be conservative we will assume for the purpose of this study the more conservative ambient dose rate limit of 15 μSv/h (for 400 hours/y). We define the design goal for limiting uncontrolled beam loss to be that amount of beam that results in a local dose rate of 15 μSv/h, 40 cm from the accelerating structure.

Table 1: Dose/Dose Rate Limits

Event/Area classification	Dose limit	Ambient dose rate limit
Normal operation	10 mSv/y	
Permanent workplace	1 mSv/y	0.5 μSv/h
Supervised temporary workplace	6 mSv/y	15 μSv/h
Controlled radiation area	20 mSv/y	50 μSv/h

COMPUTATIONAL METHOD

The radiological studies below are based on Monte-Carlo simulations of proton interactions and radiation transport in the RFQ and DTL using the MARS program [5 - 7]. For the purpose of calculating the activation we have constructed simple models of both the RFQ and DTL that represent the geometry and parent materials used in their fabrication. In all cases we have assumed as a source of lost beam a 1 watt beam of protons, having trajectory perpendicular to the surface, incident at a single point on the inner surface of the accelerating structure. We used the MARS code to calculate the residual equivalent dose rate on the outer surface of the model and at various distances from the surface. The residual dose rates are directly proportional to the power of the incident proton beam so from these calculations we can derive the beam power required to meet the dose rate limit discussed above.

We have attempted to duplicate the activation expected during a maintenance period following a typical run cycle. In all examples we have assumed a 100 day run in which the accelerator structure is exposed to a 1 W point source of protons followed by a cool-down period.

RFQ

The ESS RFQ is designed to accelerate protons, having an average beam current of 2.5 mA, from 75 keV to 3 MeV. Modern high performance RFQs are typically fabricated from brazed oxygen-free electronic grade (OFE) copper with possible stainless steel flanges. Figure 1 shows the typical RFQ cross section of such RFQ. performance RFQ.

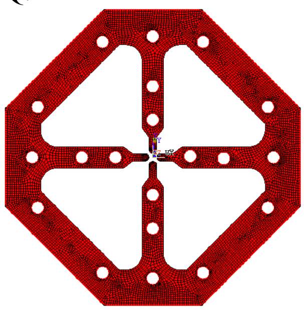

Figure 1: Typical cross section of a modern RFQ.

Beam loss in RFQs typically occurs when the injected proton beam is mismatched to focusing lattice. When protons fall out of synchronism with the rf and are no longer accelerated they will typically be transported without further acceleration to the end of the structure. Protons that escape transverse confinement will typically strike either the outer wall or end wall of the structure. The walls of the RFQ are typically ~ 5 cm thick. The RFQ model for our MARS calculations is a Cu cylinder 20 cm in diameter with a 5 cm wall thickness. Figure 2 shows expected surface activation and dose rates at 40 cm for 100 days of irradiation followed by 4 hours of cool-down time.

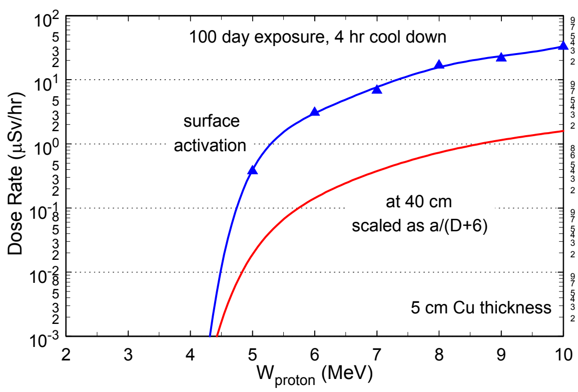

Figure 2: Expected surface dose rates and dose rates at 40 cm from the RFQ.

Since expected activation is directly proportional to the power of the lost protons, we can derive the design limit for beam loss as a function of incident protons energy, applying our ambient dose rate limit of 15 µSv/h to the radiation field on surface and 40 cm from the surface of the RFQ. Figure 3 shows both the beam loss limit in units of average power and beam current that would result in an ambient dose rate of 15 µSv/h.

Applying either criteria, surface activation or the ambient dose rate at 40 cm, we can see that the limiting current for beam lost at 3 MeV is essentially unlimited. Applying the ambient dose rate limit, the average beam loss at 5 MeV would be limited to ~ 800 W or ~ 160 µA at a single point. Applying the much more conservative criteria of limiting the surface activation, the average beam loss at 5 MeV would be limited to ~ 40 W or ~ 8 µA at a single point.

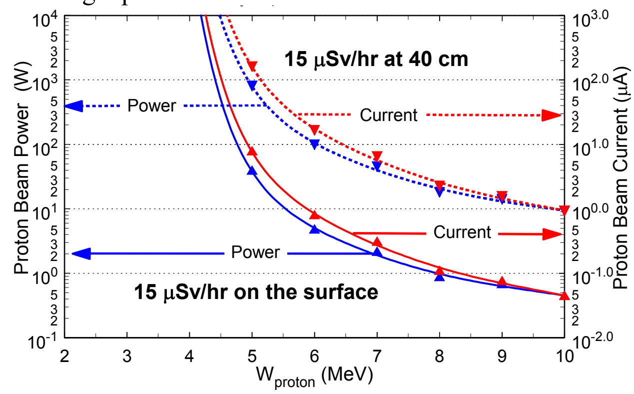

Figure 3: Power and current of lost protons required to activate the RFQ surface to 15 µSv/h and produce an ambient dose rate of 15 µSv/h at 40 cm.

DTL

To simulate the activation in the DTL we have constructed a realistic model of drift tubes that scale with proton energy. Figure 4 shows the computational model used in our MARS calculations. The drift-tube body scales in length with the velocity of the beam while the permanent magnet quadrupole (PMQ) remains constant length. The PMQ is comprised of segments of sintered permanent-magnet material enclosed in a stainless steel holder. Each drift tube has a water cooling channel.

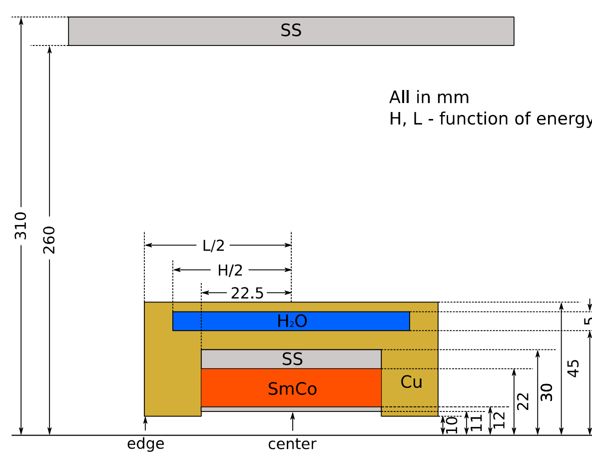

Figure 4: Computational model for the ESS DTL.

Figure 5 shows the expected surface activation of the DTL and dose rates at 40 cm as a function of energy of protons lost on the drift tube. The results shown are for protons lost on the drift tube nose, which appeared to be slightly higher than that if the protons were lost in the middle of the tube. The surface activation for energies below 30 MeV is so low as to be irrelevant for this study.

ISBN 978-3-95450-122-9

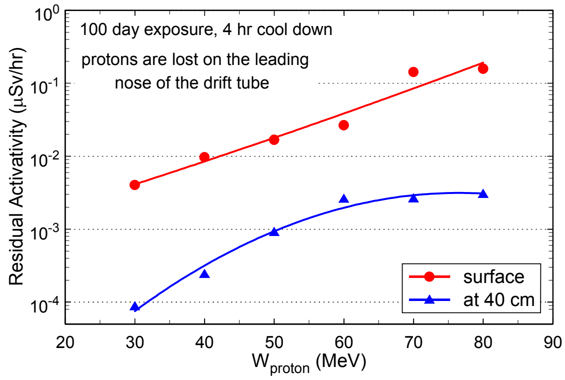

Figure 5: Residual dose rate at the surface and 40 cm from the surface of the DTL as a function of proton energy.

The above calculations were carried out assuming a 1 W proton source. Because the residual surface activity is directly proportional to the power of the protons of a given energy lost at a point on the inner surface of the accelerator we can, by normalizing the residual activity to 15 µSv/h, derive the corresponding power of the lost protons, as a function of energy, required to activate the DTL to this level. Figure 6 shows the beam power and average current required to activate the surface of the DTL to 15 µSv/h and produce an ambient dose rate of 15 µSv/h at 40 cm from the surface. It also shows the corresponding average beam current limits.

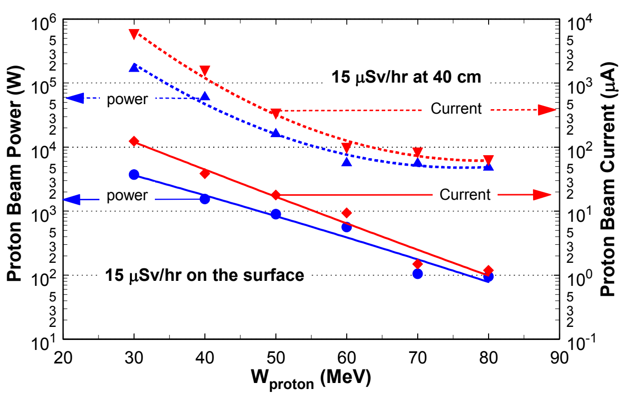

Figure 6: Beam power and current of protons lost at a point required to activate the DTL surface to 15 µSv/h and produce ambient dose rate of 15 µSv/h at 40 cm.

CONCLUSIONS

We conclude from this study that beam loss in the ESS RFQ is expected to be of no consequence. Likewise beam loss in the DTL at energies below 30 MeV is expected to be of no consequence. By setting the surface activation limit to 15 µSv/h we find that the allowable beam loss above 30 MeV can be defined by a simple exponential function of energy (Figure 7).

The limiting power loss (Figures 3 and 6) has been conservatively redefined (in Figure 7) in terms of linear power density and the corresponding current density by assuming a single point-source lost proton power limit, but distributing it over a meter [8].

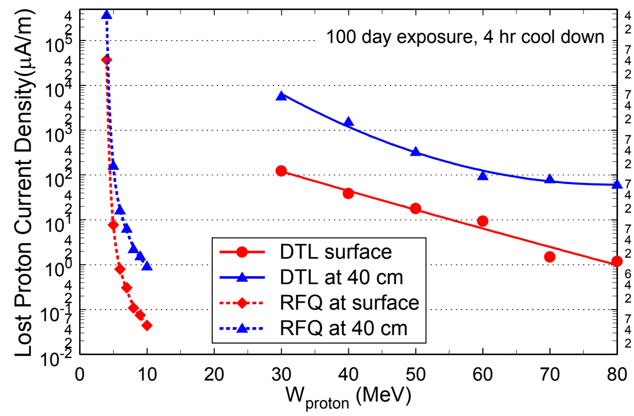

Figure 7: Average linear current density of lost protons required to activate the linac surface to 15 µSv/h and the current density required to produce an ambient dose rate of 15 µSv/h, 40 cm from the surface.

Following this design guideline assures us that the radiation environment in the linac tunnel due to activated accelerator components will meet the criteria for limited (≤ 400 hours/y) access to radiation workers for routine maintenance without the necessity of detailed job or dose planning. We further observe however in Figure 7 that the ambient dose rate 40 cm from the surface is expected to be about one tenth of the surface activation (~ 1.5 µSv/h) at all energies. This guideline therefore meets even the most conservative ESS exposure limit for "normal operations" of 10 mSv/y or 5 µSv/h for 2000 work hours if measured at 40 cm from the surface.

It is important to note that this guideline applies only to exposure from activated components that radiation workers might receive during routine but infrequent maintenance periods after the accelerator has been shut down for ≥ 4 hours. Longer interventions may require longer cool-down periods. It does not apply to exposure from prompt radiation sources nor does it apply to uncontrolled areas accessible to untrained workers.

REFERENCES

[1] Swedish Radiation Safety Authority Regulatory Code SSMFS:2008:51 ISSN 2000-0987.
[2] P. Jacobsson, "General Safety Objectives for ESS", EDMS 1148774, 2011.
[3] IAEA Sustainable Development, Nuclear Power, Fig. National Background Radiation Exposure – Western Europe.
[4] Regles Generales d'Exploitation – Area Classification, General Safety Instruction, EDMS 810149, 2006.
[5] N.V. Mokhov, "The MARS Code System User's Guide", Fermilab-FN-628, 1995.
[6] N.V. Mokhov, S.I. Striganov, AIP Conf. Proc. 896, pp. 50-60, 2007.
[7] http://www-ap.fnal.gov/MARS/.
[8] L. Tchelidze and J. Stovall, "Estimation of Residual Dose Rates and Beam Loss Limits in the ESS Linac", ESS AD technical note ESS/AD/0039, 2012.