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Long-term residual radioactivity in an intermediate-energy proton linac

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ABSTRACT

A new 160 MeV H^- linear accelerator (LINAC4) is being installed at CERN to replace the present 50 MeV LINAC2 as proton injector of the PS Booster (PSB). During operation, the accelerator components will be activated by the beam itself and by the secondary radiation field. Detailed Monte Carlo simulations, for various beam energies and several decay times, were performed to predict the residual radioactivity in the main accelerator components and to estimate the residual dose rate inside the tunnel. The results of this study will facilitate future dismantling, handling and storage of the activated parts and consequently minimize the radiation dose to involved workers. The component activation was also compared with the exemption limits given in the current Swiss legislation and to the CERN design values, in order to make predictions for the future storage and disposal of radioactive waste. The airborne radioactivity induced by particles escaping the beam dump and the activation of the beam dump cooling water circuit were also quantified. The aim of this paper is to provide data of sufficiently general interest to be used for similar studies at other intermediate-energy proton accelerator facilities.

1. Introduction

The estimation of the induced radioactivity in an accelerator facility is particularly important for maintenance interventions and the final disposal of radioactive waste. Safety is the main reason to perform a radiation protection study already during the design and construction phase. It must be demonstrated that the ALARA (As Low As Reasonable Achievable) principle has been taken into account in the design of the new facility. Components that could be activated must be designed in such a way as to facilitate their dismantling, handling and storage in order to minimize the radiation dose to workers.

LINAC4 is a new 160 MeV H^- accelerator which in a few years will be the source of protons for all accelerators at CERN. It is an 80-m long normal-conducting linac made of an H^- source, a Radio Frequency Quadrupole (RFQ), a chopping line and a sequence of three accelerating structures: a Drift-Tube Linac (DTL), a Cell-Coupled DTL (CCDTL) and a Pi-Mode Structure (PIMS) [1,2]. LINAC4 will operate at 1.1 Hz, with a peak current of 40 mA and a pulse length of 0.4 ms as Proton Synchrotron Booster (PSB) injector. These parameters correspond to 0.08% beam duty cycle and 0.032 mA average current or 2×10^{14} protons/s, equivalent to a beam power of 5.1 kW at the top energy of 160 MeV. LINAC4 has been designed to replace the present 50 MeV LINAC2 as injector of the PSB. The higher injection energy will allow the production by the PSB of beams with increased brightness as required by the High-Luminosity LHC (Large Hadron Collider). LINAC4 accelerating structures have also been designed to be the front-end of a future high-power Superconducting Proton Linac (SPL) [3].

LINAC4 is terminated by a dump collecting the beam which is not intended for further utilisation. When the beam interacts with the dump, hadronic interactions produce mixed radiation fields with large numbers of neutrons and other highly penetrating particles. Moreover, the material of the dump becomes highly activated. In addition, the LINAC4 accelerator complex is built in such a way (e.g. depth and orientation of the tunnels) that it allows a future possible connection to the SPL. Consequently, the dump will not be integrated inside the wall as it is a common solution in similar facilities, but it will be placed at the junction between the accelerator and the transfer tunnel (Fig. 1). Therefore an effective shielding surrounding the dump is needed in order to limit activation of the adjacent structures and to protect the personnel accessing the machine.

Activation of the accelerator components at energy between 3 and 160 MeV generates a large volume of (mostly weakly) radioactive stainless steel and copper, which also include permanent magnetic quadrupoles made of a samarium–cobalt alloy. These

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components will be subjected to very different levels of activation, depending on the beam loss patterns, on the type of material and on the geometry.

2. Overview of literature data

Various radiation protection studies for new linear accelerator facilities have been published in recent years. Popova et al. [4,5] calculated the expected residual dose rates for commissioning stages and maintenance work at the US Spallation Neutron Source (SNS) accelerator facility. Ene et al. and Tchelidze and Stovall [6,7] performed a first estimate of the shielding required for the superconducting linear accelerator of the European Spallation Source (ESS). They also provided a preliminary characterisation of the residual radioactivity inside the accelerator tunnel for routine maintenance. Nakashima et al. and Yamamoto [8,9] provided beam loss estimations and dose rate calculations for the radiation shielding design of the Japanese high-intensity proton accelerator project (J-PARC). Ferrari et al. [10] used Monte Carlo simulations for optimising some aspects of the shielding of the MYRRHA proton beam line.

Most of these studies focus on shielding design and operational radiation protection requirements. Ene et al. [6] and Ferrari et al. [10] provide dose rate maps and information on the produced radionuclides, but at much higher energies than the present study. This paper discusses in detail extensive calculations of the residual radioactivity in CERN LINAC4, performed in view of its decommissioning at the end of its operational lifecycle. Dose rates were estimated after 30 years of operation for several cooling times up to 2 years. The induced radioactivity and the full radionuclide inventory were assessed in the main components of the three accelerating sections and in the beam dump, for cooling times ranging between 1 day and 500 years. The estimations of the airborne radioactivity, cooling water activation, committed effective dose for the beam dump are discussed in detail. Complete information on beam loss assumptions, accelerator structures and dump components are also provided.

The aim of this paper is to provide data and guidelines that can be of use for estimating the residual radioactivity (both in terms of dose rates and radionuclide composition) in proton accelerators of similar energies, not necessarily linacs. Apart from linear accelerators used e.g. as injectors to high-energy machines, it should be considered that there is an increasing number of 200–250 MeV proton accelerators being installed in hospitals worldwide for cancer radiation therapy [11,12]. These machines are either synchrotrons or cyclotrons, but proton therapy linacs are also under development [13,14]. The results presented in this paper can easily be scaled by the beam loss rate (number of lost particles per unit time).

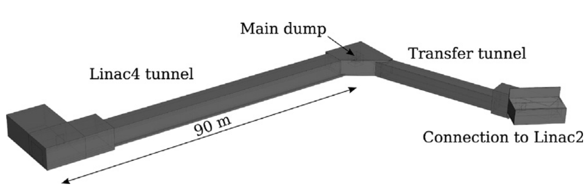

Fig. 1. Layout of the LINAC4 underground tunnel complex.

3. FLUKA calculations

Monte Carlo models used to estimate induced radioactivity in accelerator components must be able to reliably predict nuclide production in arbitrary target elements and for neutron energies ranging from thermal to a value close to the maximum accelerator energy. In this study the Monte Carlo code FLUKA [15,16], which is an appropriate code for estimating induced radioactivity in a wide range of accelerator facilities [17], was used.

Since the statistical uncertainty of the FLUKA simulations on the calculated values is within a few per cent, they are not quoted in tables and figures. The estimation of a systematic error to the hadronic interaction model is very difficult, since there is not always the possibility of comparing predictions to experimental data. The existing data point out that, on average, the agreement of FLUKA predictions of data is at level of about 10% [18].

3.1. Beam loss assumptions and irradiation profile

In a linear accelerator the equipment activation is produced by scattered particles escaping from the fields generated for controlling beam focusing and acceleration and hitting the vacuum chamber. It is hard to predict and identify the beam loss locations because they will not be equally distributed along the machine. Losses typically occur in the aperture restrictions of quadrupoles, due to the possible mismatch between linac sections. According to the estimated particle loss distribution, it was assumed that constant losses of 0.1 W occur every 10 m at selected points along the machine. This value comes from the analysis of the beam losses [19] for a 6% duty cycle scenario, indicating a maximum loss of 1 W in some ”hot spots”. During the LINAC4 operation as PSB injector at 0.033% duty cycle, losses would be theoretically reduced by a factor of 180 although it is expected that the sensitivity of the beam loss monitors would not allow reaching such a low loss level. A conservative value of 0.1 W per loss location was therefore assumed, 18 times higher than the minimum achievable loss level [20]. Table 1 shows the seven beam losses for the three main accelerating structures with a total length of 70 m. It is evident that with increasing energy the number of lost particles decreases for constant lost beam power. The calculation of the induced radioactivity was performed in three positions (noted in bold in Table 1), representative of typical aperture restrictions in the various sections of LINAC4: the first drift tube of the third DTL tank at 31 MeV, the quadrupole at 80 MeV within the CCDTL section and the last quadrupole at 155 MeV within the PIMS section. For each position the calculations took into account the activation due to the two loss points upstream and downstream of the one under study, a rather innovative approach in this type of study.

The induced radioactivity depends on the irradiation profile, which includes periods of operation at various beam intensities alternating with shutdown (maintenance) periods. Although the LINAC4 irradiation profile during its 30 years of planned operation

Table 1
Beam loss assumptions along the main accelerating structures. The three activation study points are shown in bold.

	DTL		CCDTL		PIMS		
Distance (m)	4	**12**	23	**35**	45	55	**66**
Energy (MeV)	11	**31**	57	**80**	100	128	**155**
Beam loss (p/s)	5.67E+10	**2.01E+10**	1.09E+10	**7.80E+09**	6.24E+09	4.88E+09	**4.03E+09**