MODELLING THE RADIOACTIVITY INDUCED BY SLOW EXTRACTION LOSSES IN THE CERN SPS

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Abstract

Resonant slow extraction is used to provide an intense quasi-DC flux of high-energy protons for the Fixed Target (FT) physics programme at the CERN Super Proton Synchrotron (SPS). The unavoidable beam loss intrinsic to the extraction process activates the extraction region and its equipment. Although the radiation dose to equipment has an impact on availability, the cool-down times required to limit dose to the personnel carrying-out maintenance of the accelerator also pose important restrictions, and ultimately limit the number of protons on target. In order to understand how the extracted proton flux affects the build-up and subsequent cool-down of the induced activation, a model based on a simple empirical relationship has been developed and shown to predict the measured radioactive decay at ionisation chambers located along the extraction region. In this contribution, the empirical model is described, its strengths and limitations discussed, and its application as a predictive tool for estimating cool-down times as a function of extracted proton flux demonstrated.

INTRODUCTION

The resonant slow extraction process using an electrostatic septum is an intrinsically lossy process, inducing unavoidable activation of the extraction region and its equipment. In the mid-1990's dedicated measurements of the induced radioactivity (IR) of the Long Straight Section (LSS) 6 extraction region were first carried out to understand the build-up of activation during the high intensity operation of the West Area Neutrino Facility (WANF) [1–3]. Between 1993 and 1998 the intensity of the 440 GeV proton beam was ramped up to unprecedented levels, achieving the annual record for resonant extraction at the SPS of over 1.9×10^{19} protons on target (POT). During this period an empirical model was developed to fit the measured data as a function of the extracted proton flux, allowing predictions of cool-down times to be made during operation.

Today, protons are extracted at 400 GeV to the North Area (NA) through LSS2 using a third-integer resonant slow extraction. The extraction system in LSS2 is composed of 5 electrostatic wire septa (ZS) that deflect the resonantly excited beam into the downstream extraction channel composed of magnetic septa (MST and MSE). The extraction equipment is shown in Fig. 1, along with the instrumentation relevant to this study. Beam Loss Monitors (BLMs) placed along the extraction region are used to measure the prompt beam loss induced by the small fraction of the beam that impacts the wires of the ZS septum during extraction. In addition to the BLMs, a series of ionisation chambers (PMIUs) are used to measure the IR. Unlike the BLMs, the PMIU detectors have a fixed gain and saturate during extraction due to the high prompt loss signal but give a reliable signal during periods of cool-down.

In light of tightening limits on dose to personnel and recent requests for increased intensities, as well as ambitious future experimental proposals in the NA, such as the SPS Beam Dump Facility (BDF) [4], the empirical model was revived and further developed using the instrumentation installed in LSS2 [5]. The objective of this work was to estimate the cool-down times required for the POT requested by the NA in 2017 and to estimate the improvement in the extraction efficiency required to keep cool-down times for the future BDF reasonable; the BDF is requesting 20×10^{19} POT over 5 years, compared to the 7×10^{19} POT delivered to WANF over a similar duration.

EMPIRICAL MODELS OF IR(t)

One of the most challenging aspects of predicting the evolution of the IR is the non-linear time dependence of its effective half-life arising from the mixture of different radionuclides produced both during the initial irradiation and in the resulting chains of radioactive decay. After irradiation, the exponential decay of the IR can be expressed as,

$$\mathrm{IR}(t) \propto \exp\left(-\frac{t}{\tau(t)}\right) \quad (1)$$

where different functional forms for the time evolution have been proposed [1]. The most suitable model at the SPS was shown empirically to take the above exponential form with,

$$\tau(t) = \frac{t}{k_1 \ln(t)^{k_2}} \quad (2)$$

where k_1 and k_2 are decay constants. By differentiating Eq. 1 with respect to time and re-writing the result as a first-order linear ordinary differential equation one can write the effective half-life of the empirical model by inspection as,

$$t_{1/2}(t) = \frac{t}{k_1 k_2 \ln(t)^{k_2-1}} \ln(2) \quad (3)$$

A similar derivation based on another empirical model developed by Sullivan and Overton can be found in [7]. As one would expect for a physical effective half-life describing a mixture of different radioisotopes, each with different populations and half-lives, the expression continually increases at an exponentially slower rate towards stability, i.e. $\lim_{t\to\infty} t_{1/2}(t) = \infty$ and $\lim_{t\to\infty} \frac{\partial t_{1/2}(t)}{\partial t} = 0$, for

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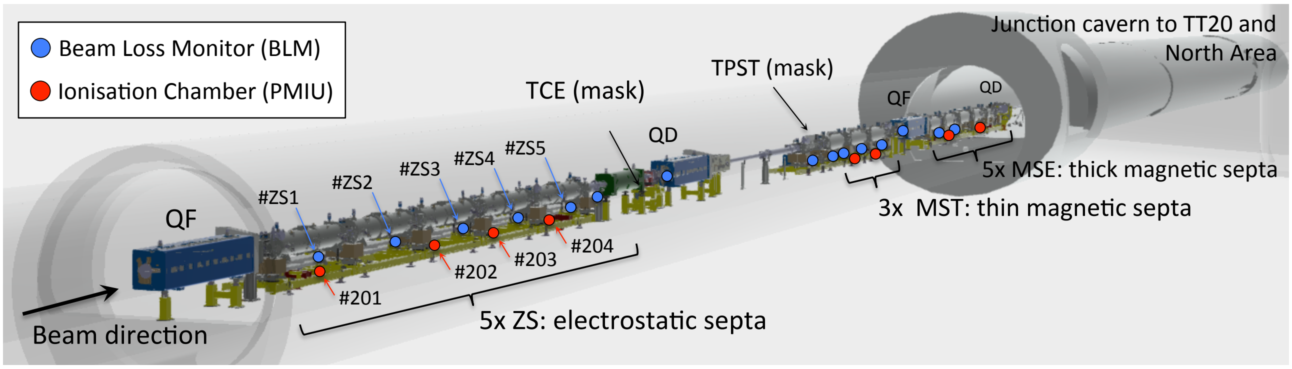

Figure 1: LSS2 slow extraction region towards the TT20 transfer line and the NA [6].

$k_1, k_2 \in \mathbb{R}_{>0}$ and $k_2 > 1$, which is not the case for many of the empirical models that have been proposed to date [8, 9]. A few different models are compared in Fig. 2 with the measured effective half-life extracted from the data logged on the PMIU.202 detector located next to the ZS2 tank during a week-long stop in operation in 2016.

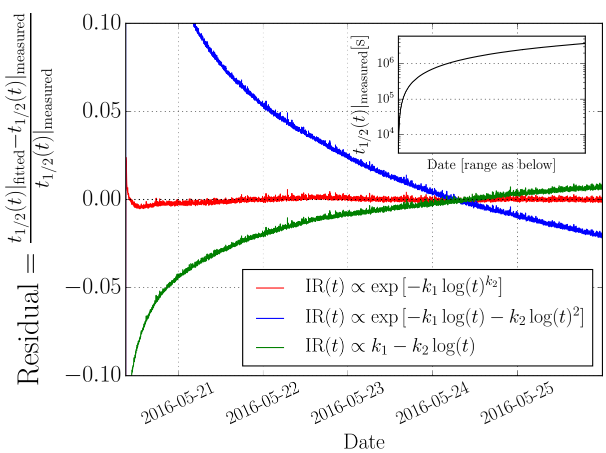

Figure 2: Fit residuals for different models of $t_{1/2}(t)$ using the measured IR decay on PMIU.202 in LSS2.

The fitting was also carried out on simulated data generated by activating different materials with a 400 GeV proton beam for 200 days using the ActiWiz code [10]. The fit constants showed good agreement with the simulated activation of stainless steel, which is the dominant material component of the ZS, and also with the fit constants attained empirically.

A predictive model of the build-up and decay of the IR was developed as a function of time by introducing the measured extracted proton flux $P_{\mathrm{ex}}(t)$ and the prompt normalised loss per proton $N_L(t)$. The introduction of N_L, as measured on the BLMs next to the ZS, was an attempt to introduce changes in the extraction efficiency into the model. The model was discretised in time, using bins of duration Δt, and an exponential decay function generated at every bin with a starting value proportional to both P_{ex} and N_L. At the n^{th} bin the IR can be expressed as a sum of exponentials arising from all previous bins according to,

$$\mathrm{IR}_n = G \sum_{i=1}^{n} N_{L,n+1-i} P_{\mathrm{ex},n+1-i} \exp\left(- k_1 \ln(\Delta t (i-1))^{k_2} \right)$$

where G is a constant conversion factor that depends on the primary beam energy, material composition and geometry of the machine, including the relative positions of the detectors and their calibrations. This relatively simple analytic function depends on only three constants determined empirically by applying a non-linear least-squares fitting routine on logged measurement data taken during past operational years. An example is shown in Fig. 3 using data logged

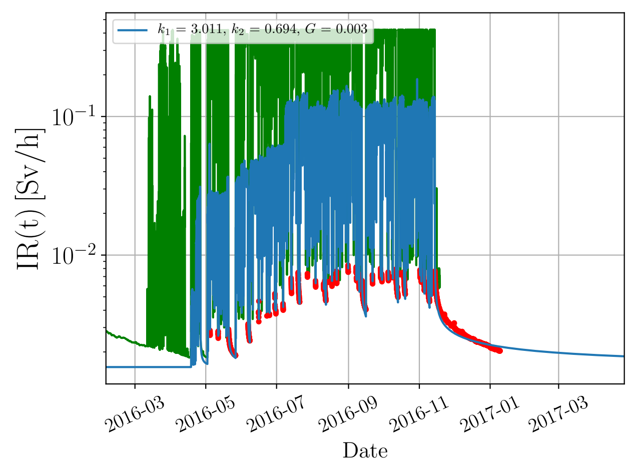

Figure 3: IR model (blue) fitted to measured filtered data (red): first 5 h of data after beam stops and saturated data are filtered from the raw data (green), $\Delta t = 0.5$ h.

during 2016. In this example, PMIU.202 was paired with its closest BLM on ZS2 in order to account for variations in the extraction efficiency. The agreement between measurement and the fit is better than 10% from a few days to 2 months of cool-down. The IR measured on the PMIU detectors has to be filtered to remove saturated values acquired in the presence of beam, as well as data taken immediately after a stop in operation. The quality of the fitting over longer time

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periods is limited by the fast initial variation of the half-life caused by the rapid decay of short-living radioisotopes and the length of the stops during the operational year over which the fitting is made. The fit convergence is improved significantly if the first few hours of data is removed; the amount of data removed is a free parameter chosen to improve the fitting in the time range of interest.

The fit constants determined from the logged 2016 data are shown in Table 1 by pairing each PMIU with its nearest BLM. The variation in G can be attributed to the relative positions and differences in calibration of the PMIUs and BLMs. The variations in the decay constants k_1 and k_2 indicate localised differences in the decay rate. A spatial dependence of the cool-down rate is indeed observed along LSS2 and is likely caused by local differences in the material composition of the equipment in proximity to the detectors. The effect is most prevalent in the first days of cool-down. The fitting was also carried out on the average of all detectors next to the ZS to give a more global description of the IR, from which similar fit constants were also attained.

The predictive power of the model was tested on data logged in 2011 and 2015 by applying the 2016 fit constants. The discrepancy with the model was tested using PMIU.202 and BLM.ZS2, and was again accurate to within 10%.

Table 1: Empirical Constants Determined from 2016 Data

BLM.ZS # $N_L(t)$ [Gy/p]	**PMIU #** IR(t) [Sv/h]	k_1	k_2	G [Sv/h/Gy]
1	201	3.14	0.69	0.0062
2	202	3.01	0.69	0.0027
3	203	2.73	0.66	0.0007
4	204	2.44	0.76	0.0008
average	average	3.31	0.67	0.0016

FUTURE OPERATIONAL SCENARIOS

During the shutdown period early in 2016 two ZS tanks had to be exchanged for preventative maintenance due to problems observed in 2015. Using the actual dose taken by the personnel involved in these interventions and the measured IR as a reference, the dose for given cool-down times was estimated for future operational scenarios. In the following estimates the cool-down times are quoted at the end of an operational year for a 5 mSv collective dose using the exchange of ZS tank 2 on 19th February 2016 as the reference; the collective dose taken was 1.7 mSv after 100 days of cool-down.

An intensity profile $P_{\text{ex}}(t)$ based on the draft 2017 CERN Injector Schedule was assumed and parameterised by the number of spills per day (SPD), protons per pulse (PPP) and N_L, where the extraction efficiency is inversely proportional to N_L. The cool-down times parameterised in terms of SPD and N_L are shown in Fig. 4 for an intensity of 4×10^{13} PPP, as requested by both the NA in 2017 and the future SPS BDF. In this case a model pairing PMIU.202 with BLM.ZS2 was used. The cool-down times scale almost quadratically with N_L and intensity.

In 2017, an average of 3300 SPD is predicted, whereas for the BDF over 6000 SPD would be needed to meet the requested POT. Considering the same average extraction efficiency as measured on BLM.ZS2 in 2015 ($N_L = 1.8 \times 10^{-14}$ Gy/p) one can consider cool-down times of approximately 17 days. For the SPS BDF the cool-down times would extend to over 7 weeks with today's extraction efficiency. An improvement of at least a factor 3 is required in order to keep future waiting times below a week during operation of the BDF.

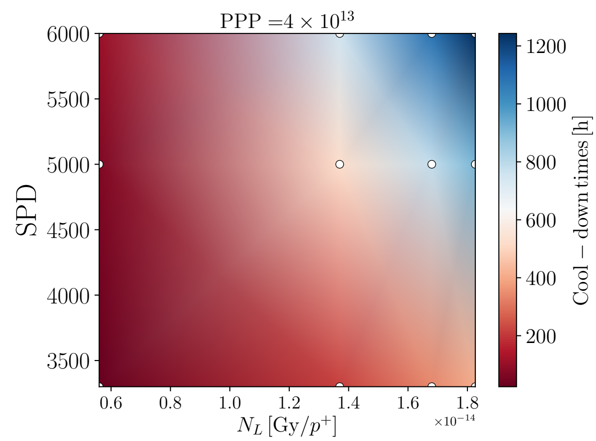

Figure 4: Parametric study of waiting times for the reference intervention: ZS2 tank exchange at 5 mSv collective dose.

CONCLUSION AND OUTLOOK

An empirical model was used to estimate the cool-down times for interventions on the ZS septa in LSS2 for future operational scenarios. The estimates assume that the shape of the activation profile along LSS2 does not change significantly and that no local hotspots arise. As observed in recent operation, localised hotspots could significantly affect the dose taken during interventions and the conclusions made with the aforementioned assumptions should be taken with care. The model provides a powerful tool to understand changes in the activation levels as a function of the extracted proton flux and extraction efficiency, which could permit the identification of hotspots before their identification in the end of year radio-protection survey.

Further work is needed to understand the build-up of the induced radioactivity from longer-living radioisotopes over extended periods of operation and to tune the model to the these timescales. In addition, further study is needed to understand the interdependence of the extraction efficiency, the prompt beam loss and resulting IR. To this end, the LSS2 geometry is being implemented into the FLUKA code [6,11] to generate loss and activation maps.

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