SPS SLOW EXTRACTION LOSSES AND ACTIVATION: CHALLENGES AND POSSIBILITIES FOR IMPROVEMENT

M.A. Fraser*, R.G. Alia, B. Balhan, H. Bartosik, C. Bertone, D. Björkman, J. Borburgh, N. Conan, K. Cornelis, L. Gatignon, B. Goddard, Y. Kadi, V. Kain, A. Mereghetti, F. Roncarolo, P.M. Schicho, J. Spanggaard, O. Stein, L. Stoel, F.M. Velotti, H. Vincke, CERN, Geneva, Switzerland

Abstract

In 2015 the highest integrated number of protons in the history of the North Area (NA) was slow extracted from the CERN Super Proton Synchrotron (SPS) for the Fixed Target (FT) physics programme. At well over 1.1×10^{19} protons on target (POT), this represented the highest annual figure at SPS for almost two decades, since the West Area Neutrino Facility was operational some 20 years ago. The high intensity POT requests have continued into 2016 - 17 and look set to do so for the foreseeable future, especially in view of the proposed SPS Beam Dump Facility (BDF) and experiments, e.g. SHiP [1], which are requesting up to 4×10^{19} POT per year. Without significant improvements, the attainable annual POT will be limited to well below the total the SPS machine could deliver, due to activation of accelerator equipment and associated personnel dose limitations. In this contribution, the issues arising from the recent high activation levels are discussed along with the steps taken to understand, manage and mitigate these issues. The research avenues being actively pursued to improve the slow extraction related beam loss for present operation and future requests are outlined, and their relative merits discussed.

INTRODUCTION

The SPS presently provides beam to the NA FT physics programme via a third-integer resonant slow extraction with a spill length of several seconds. The extraction system is located in Long Straight Section (LSS) 2 and is composed of an electrostatic septum (ZS) upstream of magnetic septa (MST and MSE), as shown in Fig. 1.

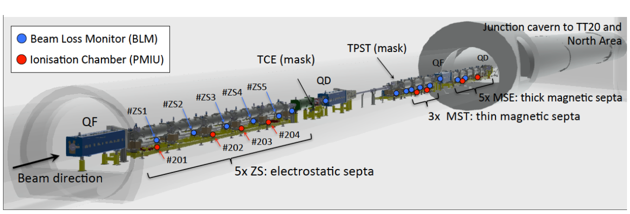

Figure 1: LSS2 slow extraction region [2].

The ZS is divided into 5 separate tanks, 3.1 m in length, each containing an array of 2080 W-Re wires that create the boundary delimiting the low and high electric field regions. The wires are made as thin as possible (ZS1-2: 60 μm diameter, ZS3-5: 100 μm diameter) in order to reduce beam losses, but a small fraction of beam is unavoidably scattered on the wires, inducing radioactivity in LSS2. The slow extracted beam is distributed via a network of transfer lines in the NA and delivered simultaneously to multiple experimental targets by splitting the beam directly on steel Lambertson septa magnets [3]. This process, when combined with the extraction and transfer efficiency, introduces losses from ring to targets that typically sum to 30 %. This includes the beam left in the SPS at the end of the spill, which is dumped internally on a dedicated absorber.

PRESENT AND FUTURE CHALLENGES

Machine Reproducibility

Nowadays the SPS is a truly multi-cycling machine delivering different beams to multiple users in a single super-cycle, the composition of which changes many times per day. In parallel to delivering proton and ion beams to the NA for FT physics, and in-between regular fills of the LHC, beams are also provided to the HiRadMat irradiation facility [4], the AWAKE plasma wakefield facility [5] and to Machine Development (MD) users who often fill any remaining space in the super-cycle. In addition, a dynamic economy system has been introduced to save energy by ramping the main power supplies only if beam is received on the injection plateau. The frequent changes to the magnetic cycling of the machine impacts the reproducibility of the machine, the effects of which are most noticeable on the resonant FT cycle. Recent studies have shown correlation between super-cycle changes and the effective spill length and mean closed-orbit [6, 7]. The degradation of the reproducibility is also observed in the stability of the extraction losses measured on Beam Loss Monitors (BLMs) located in LSS2. There is evidence to suggest that the hysteresis, which amounts to just a few Gauss at flat-top, is responsible for these variations on timescales of hours.

In addition to the hysteresis effects, the longer term stability of the closed-orbit in the bending plane of the synchrotron has been shown to drift by over a mm on timescales of several weeks in the LHC extraction regions of the SPS [8]. This makes it very difficult to maintain the relative alignment between the ZS and the beam, demanding regular realignment of the septa, which is presently a lengthy procedure. The source of the drift has not yet been identified.

In 2016, the source of a recurrent glitch on the main quadrupole circuit was tracked down and repaired, which has since markedly improved the spill quality [7].

Extraction Inefficiency

A concerted simulation effort is presently underway to model the extraction process using MADX combined with

* mfraser@cern.ch

ISBN 978-3-95450-182-3

the `pycollimate` scattering routine [9] in order to produce loss maps to guide the alignment of the ZS. The objective is to build-up a simulation framework to model all of the different loss mitigation concepts proposed and to compare the relative merits of each one, or several applied in unison. First results simulating today's extraction process indicate extraction inefficiencies of close to 2% for an idealised ZS consisting of a single element with an effective thickness of 200 μm, taking into account the expected alignment tolerances. Measurements of the extraction inefficiency (losses) carried out in 2016 showed that 3.6 - 4.0% of the beam is lost between the ring and the start of the transfer line towards the NA, indicating room for improvement [10]. These studies are being followed-up by implementing the complete LSS2 extraction region in FLUKA [2, 11] to understand the nominal prompt loss map, the corresponding response of the BLMs and the expected distribution of induced radioactivity.

Monitoring and Surveillance

In mid-July of 2015 a sudden change in the prompt extraction losses measured next to the ZS went uncorrected for a significant part of the physics run. Despite the fact that the number of protons per spill and therefore prompt extraction losses were relatively moderate, the duty cycle was high and as a result the induced radioactivity accumulated. In order to prevent this from happening again interlock thresholds on the loss level normalised to the number of extracted protons were put in place on the Beam Loss Monitors (BLMs) next to the ZS, the data displayed in the online SPS Quality Control application and logged to a database. Despite best efforts in 2016 to reduce the measured beam loss at the ZS a hotspot was observed at the downstream mask (TPST) in front of the MST during the end-of-year radio-protection survey. In 2017, the monitoring was extended to all BLMs and the first ZS realignment campaign has already reduced the beam loss at the TPST.

These issues highlight the need for a better understanding of how the build-up of activation in LSS2 is linked to the measured prompt beam loss profile and intensity such that preventative measures can be taken from the control room before hotspots are discovered at the end of the year.

LSS2 Activation Levels: Today and in the Future

To assess the impact of future POT requests an empirical model of the induced radioactivity was implemented to predict the build-up and cool-down of the dose rate in LSS2 [12]. To this end, the dose to personnel taken during an exchange of a ZS tank in 2016 was used as a reference intervention and scaled according to the model's prediction of the induced radioactivity as a function of POT. The model showed an almost quadratic dependence of the cool-down times on the POT. With the extraction efficiency of 2015, the cool-down times will be pushed to over 7 weeks for acceptable dose levels and the intensity requested by the BDF. To keep the cool-down times below one week an improvement of at least a factor 3 in the extraction efficiency is required. Further work is needed to understand the build-up of the induced radioactivity from longer-living radioisotopes over extended periods of high-intensity operation.

Interventions and Remote Handling

A catalogue of interventions on the extraction equipment and corresponding dose planning has been produced in response to the elevated activation levels in LSS2, with all efforts made to reduce dose to personnel during hands-on maintenance. In 2016, two ZS tanks had to be exchanged during the shutdown for preventative maintenance due to problems observed in 2015. The cool-down time was maximised and remote handling used for the first time in LSS2 to reduce dose to personnel. Further automation and robotisation will be investigated, although this will only ever be applicable to a subset of the work in the tunnel.

POSSIBILITIES FOR IMPROVEMENT

Several possibilities to reduce dose to personnel during hands-on maintenance, which is considered the most important figure of merit, are being investigated, spanning improved SPS machine stability, manipulation and control of the extracted separatrix, diffuser elements, alternative extraction hardware concepts, low-activation materials and extended use of remote handling techniques.

B-Train Implementation

Exploitation of a calibrated real-time magnetic measurement (B-train) of an SPS reference main dipole will be indispensable to be able to feed-forward and correct changes in the magnetic history. Such a system will be deployed in the SPS from 2018 onwards [13].

Dynamic Bump

In the SPS the angular variation of the extracted separatrix for different momenta increases the number of particles intercepting the wires of the ZS during the spill. If the separatrices could be overlapped during extraction a significant reduction in losses could result; at J-PARC the implementation of a dynamic bump system for this purpose reduced losses by over a factor of 3 [14]. First simulations show a possible gain of over 20% when applied to the SPS. The dynamic bump is, however, an important prerequisite for other loss reduction methods like the passive or active diffuser, and will be tested in MD sessions planned for 2017.

Passive Diffuser

A reduction in the transverse density of the beam profile at the wires of the ZS would produce a reduction in beam loss in the extraction region. The conventional way of accomplishing this is to add a diffuser element, composed of a passive foil or array of wires accurately positioned upstream, to deliberately induce scattering in the beam with the objective of reducing the phase space density at the wires. For a diffuser comprising a 3 mm length of W-Re, an additional beam loss reduction factor of about 2 has been obtained in simulation [15], provided that a thin separatrix can be obtained with a dynamic bump.

ISBN 978-3-95450-182-3

Active Diffuser: Bent Crystals

An improvement on the passive diffuser can be conceived using a bent crystal to coherently deflect particles away from the ZS wires through a large angle [16]. The channelling efficiency depends strongly on the angular distribution of the impinging beam, which is important for the specification of the acceptable angular spread at the crystal. The active diffuser coherently deflects a large fraction of channelled beam across the septum, and a beam loss reduction factor of approximately 3.5 has been obtained in simulations assuming a single-pass channelling efficiency of 54% [17]. The challenge for this approach will be the high sensitivity to the incoming particle angular spread and offset, and ensuring that the channelled particles are properly dumped or transported to the experiment's production target.

Phase Space Folding

The use of higher-order multipoles to modify the transverse phase space distribution in such a way as to fold the separatrix and reduce the transverse density at the ZS is also being investigated [18]. The separatrix is broadened in angle, which may impact the transmission in the downstream elements and also increase the splitter losses, but for the beam to the BDF this may not be an issue. Preliminary simulations investigating decapoles indicate that a factor 2 loss reduction might be achieved with this technique. However, the integration in the SPS of a family of strong decapoles at suitable phase advances would be challenging.

Beam Transfer and Splitting

The transfer line TT20 to the NA presents several zones of rather high activation due to the large dispersion, momentum offset during the spill and the scattered beam halo transported with the extracted separatrix. Improvements in the beam instrumentation and possible addition of aperture defining collimators in specific locations is under study to reduce uncontrolled loss. The most beam loss, however, occurs at the radiation-resistant Lambertson splitter septa, which are protected by an upstream collimator. The fraction of beam lost on the splitters is about 20%, even with the very large vertical beam size generated at the septum. For the future BDF, one major advantage of the concept is that the splitters will be used in a 'switch' mode, where the beam is not split, nor shared, but steered toward the new beam line and target. The losses from the operation of the BDF in this region are therefore expected to be very low.

Extraction Hardware

As an alternative to stainless steel, the bulk of the ZS vacuum tanks and anode supports could conceivably be manufactured from a material such as aluminium or titanium to reduce activation. Preliminary estimates using the ActiWiz code [19] indicate that a reduction of a factor of 3 - 6 might be achievable with aluminium, while titanium seems comparable to steel over the timescale of decades but more problematic for eventual disposal.

Carbon nanotubes are being investigated as a possible material for the anode wires. The possible high voltage issues with carbon will need to be tested, and the robustness and mechanical stability of the wires will be a challenge. Nevertheless, preliminary simulations indicate a 25% reduction in beam loss if the W-Re anode wires are replaced by the same size 2.0 g/cm^3 carbon wires.

The precision of the motorisation of the present ZS has been improved in 2017 with a reduction in the minimum step size of the anode positioning to 50 μm. Other improvements are being investigated, such as a direct online monitoring of reference surfaces to measure the actual anodes position in real time, and to be able to accurately align the combined 15.5 m of anode even without the beam.

Bent crystals also offer exciting future applications with the potential of entirely replacing the conventional electrostatic septum with multi-crystal arrays capable of extracting beam resonantly or non-resonantly with a high efficiency [16].

Beam Instrumentation

Improvements to the ageing beam extraction instrumentation are highly desirable to be able to faster set-up and troubleshoot the extraction, as well as to monitor extraction efficiency and drifting parameters. The challenges of achieving robust, accurate and sensitive measurements of beam position, profile, losses and time structure are complex, for what is essentially a DC extracted beam.

Online Activation and Cool-Down Information

Efforts have been started to provide online information on the activation levels and expected cool-down times, based on an empirical model and normalised to the extracted intensity [12]. The predictive power of the model has been demonstrated to within 10% for stops in operation of a few days to weeks long.

DISCUSSION AND OUTLOOK

Many proposals for improving the beam loss, equipment activation and personnel dose are under active study, with the specific aim of being able to slow-extract 5×10^{19} protons per year from the SPS, i.e. 4×10^{19} protons for the BDF and 1×10^{19} protons for the rest of the NA, per year [20]. It is clear that there will not be one single solution but rather a combination of improvements, which together may achieve the factor 4 - 5 reduction desired. Interestingly, some of the methods for loss reduction, activation and personnel dose reduction can be cumulated directly, with a multiplicative gain. For example, a scenario with dynamic bump, 3 mm W-Re passive diffuser and carbon-nanotube ZS wires might hope to reduce the beam losses with respect to the present by a factor of $1.25\times2.0\times1.3\approx3$. The addition of separatrix folding or an active diffuser could potentially bring another factor 2, moving the improvement firmly into the domain needed for the BDF.

ISBN 978-3-95450-182-3

REFERENCES

[1] A. Golutvin *et al.*, "A Facility to Search for Hidden Particles (SHiP) at the CERN SPS", CERN, Geneva, Switzerland, Rep. CERN-SPSC-2015-016 (SPSC-P-350), Apr. 2015.

[2] D. Björkman, "Progress on the LSS2 FLUKA model", presented at the SPS Losses and Activation Working Group meeting, CERN, Geneva, Switzerland, 5 Apr. 2017.

[3] L.R. Evans *et al.*, "The steel septum magnets for beam splitting at the CERN SPS", in *Proc. 6th International Conf. on Magnet Technology* (MT-6), Bratislava, Slovakia, Aug. 1977, Rep. CERN-SPS-ABT-77-13.

[4] N. Charitonidis *et al.*, "HiRadMat: A high-energy, pulsed beam, material irradiation facility", in *Proc. of ANIMMA'15*, Lisbon, Portugal, Apr. 2015.

[5] E. Gschwendtner *et al.*, "The AWAKE experimental facility at CERN", in *Proc. of IPAC'14*, Dresden, Germany, June 2014, paper MOPRI005, pp. 582 - 585.

[6] F.M. Velotti *et al.*, "Investigation of The remanent field of the SPS main dipoles and possible solutions for machine operation", in *Proc. of IPAC'17*, Copenhagen, Denmark, May 2017, paper THPAB146, this conference.

[7] V. Kain *et al.*, "SPS slow extracted spill quality during the 2016 run", in *Proc. of IPAC'17*, Copenhagen, Denmark, May 2017, paper MOPIK049, this conference.

[8] F.M. Velotti *et al.*, "Analysis of the SPS long term orbit drifts", in *Proc. of IPAC'16*, Busan, Korea, May 2016, paper THPOR054, pp. 3914 - 3917.

[9] F.M. Velotti *et al.*, "SPS-to-LHC transfer lines loss map generation using pycollimate", in *Proc. of IPAC'15*, Richmond, VA, USA, May 2015, paper THPF098, pp. 3934 - 3937.

[10] M.A. Fraser *et al.*, "First measurements of SPS slow-extraction inefficiency", presented at the Machine Studies Working Group meeting, CERN, Geneva, Switzerland, 19 Aug. 2016, `https://indico.cern.ch/event/559108/`.

[11] A. Ferrari, P.R. Sala, A. Fasso and J. Ranft, "FLUKA: a multi-particle transport code", CERN, Geneva, Switzerland, Rep. CERN-2005-10, INFN/TC_05/11, SLAC-R-773, Oct. 2005.

[12] M.A. Fraser *et al.*, "Modelling the radioactivity induced by slow extraction losses in the CERN SPS", in *Proc. of IPAC'17*, Copenhagen, Denmark, May 2017, paper TUPIK086, this conference.

[13] T. Bohl *et al.*, "Functional specification for upgrade of SPS B-train", CERN, Geneva, Switzerland, Rep. EDMS 1689759, May 2016.

[14] M. Tomizawa *et al.*, "Performance of resonant slow extraction from J-PARC Main Ring", in *Proc. of IPAC'12*, New Orleans, Louisiana, USA, May 2012, paper MOPPD051, pp. 481 - 483.

[15] B. Goddard *et al.*, "The use of a passive scatterer for SPS slow extraction beam loss reduction", in *Proc. of IPAC'17*, Copenhagen, Denmark, May 2017, paper MOPIK044, this conference.

[16] W. Scandale, "Bent crystals in particle accelerators", presented at the 19th ABT Engineering Forum, CERN, Geneva, Switzerland, 28 Nov. 2014, `https://indico.cern.ch/event/345193/`.

[17] F.M. Velotti *et al.*, "Reduction of resonant slow extraction losses with shadowing of septum wires by a bent crystal", in *Proc. of IPAC'17*, Copenhagen, Denmark, May 2017, paper MOPIK050, this conference.

[18] L. Stoel *et al.*, "Phase-space folding studies for beam loss reduction during resonant slow extraction at the CERN SPS", in *Proc. of IPAC'17*, Copenhagen, Denmark, May 2017, paper MOPIK046, this conference.

[19] H. Vincke and C. Theis, "ActiWiz - optimizing your nuclide inventory at proton accelerators with a computer code", Progress in Nuclear Science and Technology, vol. 4, pp. 228 - 232, Apr. 2014.

[20] R. Jacobsson *et al.*, "A new Experiment to Search for Hidden Particles (SHiP) at the SPS North Area", CERN, Geneva, Switzerland, Rep. EN-DH-2014-007 (EDMS 1369559), July 2014.