ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPMP031

SPS SLOW EXTRACTION LOSSES AND ACTIVATION: UPDATE ON RECENT IMPROVEMENTS

M.A. Fraser*, R.G. Alia, B. Balhan, H. Bartosik, J. Bernhard, C. Bertone, D. Björkman, J. Borburgh, M. Brugger, N. Charitonidis, N. Conan, K. Cornelis, Y. Dutheil, L.S. Esposito, L. Gatignon, C.M. Genton, B. Goddard, C. Hessler, Y. Kadi, V. Kain, A. Mereghetti, M. Pari, M. Patecki, J.P. Prieto, S. Redaelli, F. Roncarolo, R. Rossi, W. Scandale, N. Solieri, J. Spanggaard, O. Stein, L.S. Stoel, F.M. Velotti, H. Vincke, CERN, Geneva, Switzerland
D. Barna, K. Brunner, MTA Wigner RCP, Budapest, Hungary

Abstract

Annual high intensity requests of over 1×10^{19} protons on target (POT) from the CERN Super Proton Synchrotron (SPS) Fixed Target (FT) physics program continue, with the prospect of requests for even higher, unprecedented levels in the coming decade. A concerted and multifaceted R&D effort has been launched to understand and reduce the slow extraction induced radioactivation of the SPS and to anticipate future experimental proposals, such as SHiP [1] at the SPS Beam Dump Facility (BDF) [2], which will request an additional 4×10^{19} POT per year. In this contribution, we report on operational improvements and recent advances that have been made to significantly reduce the slow extraction losses, by up to a factor of 3, with the deployment of new extraction concepts, including passive and active (thin, bent crystal) diffusers and extraction on the third-integer resonance with octupoles. In light of the successful tests of the prototype extraction loss reduction schemes, an outlook and implications for future SPS FT operation will be presented.

INTRODUCTION

A high intensity flux of 400 GeV/c protons is slow extracted from the SPS using a third-integer betatron resonance to spill the beam over an electrostatic septum (ZS) and into the extraction channel located in Long Straight Section (LSS) 2. The beam is deflected from the ring downstream of the ZS with magnetic septa before being distributed through a network of transfer lines and split simultaneously by Lambertson septa to all primary production targets serving the North Area (NA) FT programme. Without significant improvements in the extraction and splitting efficiencies, in the future the attainable annual POT will be limited well below the total the SPS machine could deliver, due to the activation of accelerator equipment and associated personnel dose limitations. A complete description of the slow extraction system and the studies reported in this paper can be found in [3], the documentation supporting the SPS Loss and Activation Working Group [4] and other proceedings at this conference referenced herein.

Several possibilities to reduce dose to personnel during hands-on maintenance, which is considered as one of the most important figures of merit alongside machine availability, are being investigated. These span improved spill quality, manipulation and control of the extracted separatrix, alternative or upgraded extraction hardware concepts, including diffuser devices (passive and active) upstream of the ZS, low-activation materials and the extended use of remote handling techniques. Over the past three years a significant effort has been made on several fronts to conceive, design, deploy and test with beam where possible, methods to reduce the prompt extraction beam loss or to mitigate its effects through different material choice or handling.

OPERATIONAL IMPROVEMENTS

In 2018 the highest annual proton flux since the operation of the West Area Neutrino Facility [5] was slow-extracted from the SPS. Since high levels of induced radioactivity were observed in LSS2 at the end of 2015, and careful operational attention was returned to the slow extraction process, the end-of-run radioactive dose rate per extracted proton next to the ZS has returned in recent years to the historical trend line. The amelioration has been helped by the improved monitoring of relevant machine parameters with dedicated software applications able to quickly alert the operation team of anomalies in the extraction efficiency or spill quality. In addition, the operational software developments have helped ease the optimisation and control of the extraction. One notable example of the advanced level of spill control now achievable is the recent demonstration of a burst-mode extraction consisting of many consecutive millisecond pulses within a single spill, which was realised by carefully modulating and shaping the tune sweep function driving the extraction [6].

Machine Reproducibility and Stability

Through dedicated studies the understanding of the reproducibility and stability of the SPS has improved. The frequent changes to the composition of the magnetic cycle impacts the machine's reproducibility. The effects are most noticeable on the resonant FT cycle, which sees a degradation in the uniformity of the spill rate sampled at low frequency ($\ll 50$ Hz) when the magnetic cycle is changed. Investigations have shown that relative tune variations of $\sim 2 \times 10^{-4}$, which are repeatable and therefore correctable, originate from hysteresis effects in the main magnets [7].

The effect of $n \times 50$ Hz perturbations on the spill coming from ripple on the main power supplies has been well characterised for each magnet circuit and is well understood

* mfraser@cern.ch

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPMP031

through theory and simulation [8, 9]. The mains harmonics are presently measured on the extracted spill and compensated by injecting noise in counter-phase on dedicated servo-quadrupoles to cancel the effect. As of 2021 the corrections will be applied directly on the main quadrupole circuit using the new digital controller along with improvements made to the spill monitoring system.

The spikes observed on the extracted intensity at the start of the spill have been attributed to the main quadrupole power supply delivering a current that overshoots its reference function on arrival to the flat-top, which can be remedied by smoothing the transition between ramp and flat top.

Extraction Inefficiency

The slow extraction inefficiency was measured recently at 3.4 ± 0.7 %, which is almost a factor of three larger than expected [10] when the effective thickness of the ZS wire array is assumed as 200 µm. FLUKA studies of the extraction process confirm that the measured beam loss response in LSS2 is consistent with the measured poor extraction efficiency [11]. The recent tests with diffusers allowed the effective ZS thickness to be probed experimentally and the results, discussed in more detail below, confirm that it is indeed larger than expected.

Automated ZS Alignment

The ZS system consists of 5 separate septa and a total of 12 positional degrees of freedom that all need aligning accurately to the beam to optimise the extraction efficiency. The operational alignment procedure is typically slow, ineffective and carried out manually. Recently, a dedicated simulation effort was carried out to understand and compare the performance of the present procedure to other algorithms, verifying the poor and slow convergence of the present approach and supporting automatic optimisation algorithms [12, 13]. An automated alignment procedure based on a Powell optimisation algorithm was tested with beam, reducing the time needed to align the septum by over an order of magnitude [14].

Beam Instrumentation

The functional requirements of the upgraded beam instrumentation needed for future operation of slow-extracted beams have been specified [15]. Some of these requirements were already met in 2018, including the installation of new beam loss and fast intensity monitors in LSS2 and the extraction transfer line, which proved critical for the success of the tests reported next.

PROMPT EXTRACTION LOSS REDUCTION TECHNIQUES

The most promising slow extraction loss reduction techniques applicable to the SPS were selected after a thorough review of the available options [16]. In recent years, various techniques were studied theoretically before being tested and validated with beam during dedicated machine development tests. The outcome of the different R&D topics are detailed briefly in this contribution with many of them tested with beam only very recently at the end of 2018.

Presentation of the Separatrix to the ZS

The movement of the separatrix arm presented to the ZS as the tune is swept during the extraction process increases the effective angular spread of the beam and the beam loss. Suppressing this effect was identified at an early stage as a main target for improvement, as well as a prerequisite for exploiting the full potential of other loss reduction techniques, such as the diffusers.

Although first work investigated a dynamic extraction bump [17], the problem was instead solved at its source by sweeping the currents in all the machine's magnetic circuits and not only the main quadrupoles. The entire machine is ramped with a function that follows the instantaneous momentum of the on-resonance particles being extracted. As a result, the optics seen by all particles at extraction is frozen throughout the spill and the separatrix remains stationary at the ZS. The new Constant Optics Slow Extraction (COSE) process was successfully commissioned and put into operation last year, as well as being exploited for the machine development tests of the different prototype loss reduction techniques [18].

Phase Space Folding with Octupoles

The application of higher-order multipoles was studied in detail at the SPS to manipulate and reduce the density of the beam impinging the wires of the ZS at the expense of a larger emittance in the plane of extraction [19–21]. Octupoles were chosen for the proof-of-principle tests because of their abundance in the SPS lattice, which allows the resonance driving term to be increased by over a factor of 2 whilst at the same time folding the beam to keep it inside the extraction aperture. As the application of octupoles during slow extraction has potentially serious machine protection implications, a detailed procedure [22] was prepared and approved to establish safe parameters and minimise the risk to the ZS during the tests. The tests safely and successfully demonstrated the feasibility of the concept and validated the simulation tools used to design the extraction scheme. With carefully chosen multipole strengths the prompt beam loss measured at the ZS could be reduced by ~42 % [23, 24]. Further work is needed to demonstrate that the large horizontal emittance can be transported and split in the transfer line.

Passive Diffuser (Wire-array)

A passive diffuser, or pre-scatterer, built in collaboration with the Wigner Institute, Hungary, was installed upstream of the ZS in LSS2. The diffuser is composed of an array of 20 tantalum wires of ⌀200 µm spaced over a total length of 30 mm, with half the array offset by 60 µm to increase its effective thickness. The angular spread imparted by the diffuser on the beam, predominantly via multiple Coulomb scattering, reduces the downstream transverse beam density and results in an overall beam loss reduction when the ZS

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPMP031

is aligned in its shadow. More details regarding the design considerations and choices for such a device can be found reviewed in [25]. During dedicated low intensity machine tests a loss reduction of ~15 % was achieved with detailed analysis and comparison to simulation indicating a relatively large effective ZS width of 500 µm [26]. The operational capability of the diffuser at high intensity and duty cycle was demonstrated during a 23 h period where a reduction of 9.4 % was achieved with no impact on operation.

Active Diffuser (Thin, Bent Crystal)

The application of a thin, bent crystal aligned upstream of an extraction septum is a novel extraction technique investigated in recent years at CERN to significantly reduce the beam intensity impinging the ZS wires during resonant slow extraction [27–29]. To demonstrate the concept, the passive diffuser was swapped out and replaced by a prototype crystal and goniometer, which was developed specifically by the UA9 collaboration for the shadowing application [30, 31]. The crystal is 2 mm long (in the direction of the beam) and 0.8 mm thick (across the beam), mounted on a holder with a large clearance of 35 mm to allow the separatrix arm to pass unimpeded on the outside of the crystal and into the extraction channel. The crystal has a 172 µrad bending angle orientated towards the outside of the machine when aligned in channelling and -15 µrad when aligned in volume reflection. In both alignment configurations a significant reduction in the prompt extraction beam loss was demonstrated. The beam tests demonstrated a loss reduction factor of ~44 % when channeling and ~20 % when in volume reflection, along with good repeatability and a shot-to-shot stability of better than 1.2 % (rms). The measurements confirmed the relatively large effective ZS width. The operational capability of the system was also successfully verified at high intensity and duty-cycle over a 13 h period without any issues, with the crystal orientated in volume reflection.

Other Concepts

Preliminary tests with carbon nanotube (CNT) wires are planned this year to qualify their performance in a high voltage environment with a view to retrofitting the upstream ZS tanks, or installing a dedicated short electrostatic septum, with CNT wires. The application of a massless magnetic septa to fold the separatrix has also been studied [32].

Combining Loss Reduction Techniques

A loss reduction factor of over $1/0.56 \times 1/0.58 \sim 3.1$ was demonstrated by combining phase space folding with octupoles whilst shadowing the ZS with the crystal, confirming that certain loss reduction techniques can be accumulated directly with multiplicative gain, see Fig. 1.

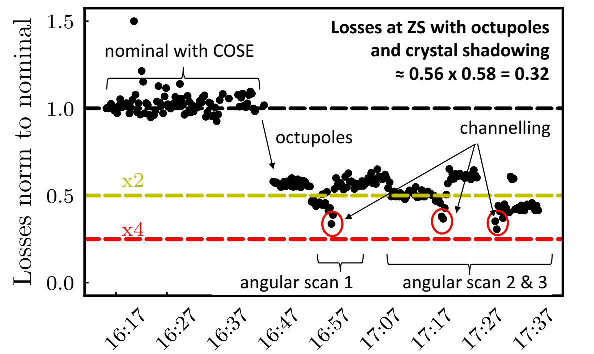

Figure 1: Evolution of beam loss measured at the ZS as the octupoles and crystal were combined on 1st November 2018.

REDUCING DOSE-TO-PERSONNEL

A FLUKA model taking into account the detailed geometry and material composition of LSS2 has been used to study the impact of alternative material choices and local shielding on the induced radioactivity and residual dose rates after beam operation [33–36]. The feasibility of implementing extraction hardware composed of alternative materials such as aluminium, titanium and carbon is being assessed and a cost-benefit analysis underway to understand how to most effectively reduce dose-to-personnel during interventions. In some cases the dose rate can be reduced by an order of magnitude with relatively simple modification such as appropriately design and proportioned shielding options. The extended use of remote handling techniques is being employed during interventions and improvements are being investigated for the future.

OUTLOOK TO FUTURE OPERATION

As a result of a concerted R&D effort the feasibility of different slow extraction loss reduction techniques have been demonstrated with recent beam tests and the NA has benefited enormously from improved machine stability, availability and spill quality from operational improvements implemented in recent years. It is clear that there will not be one single solution but rather a combination of improvements in order to achieve the slow extraction loss reduction factor of ~ 4 needed to welcome a future SPS BDF at CERN. Interestingly, it has been demonstrated that some methods for loss reduction, radioactivation and personnel dose reduction can be accumulated directly, with a multiplicative gain. The use of octupoles to fold the extracted separatrix and shadowing the wires of the ZS using a thin bent crystal are favourable options that will be actively pursued. Further studies, beam tests and optimisation of the prototype systems will be required, taking into account all aspects including stability, reliability and machine protection, and to ensure the beam can be extracted from LSS2, split and transported to the production targets. A key outcome of the recent studies is the larger than expected effective thickness of the wire-arrays in the ZS, which needs further investigation.

ACKNOWLEDGEMENT

The authors would like to thank the UA9 collaboration and Wigner Research Centre for Physics for their support and important contributions to the work presented.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPMP031

REFERENCES

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

[2] M. Lamont *et al.*, "SPS Beam Dump Facility Comprehensive Design Study", Rep. CERN-PBC-REPORT-2018-001, CERN, Geneva, Switzerland, 11 Dec 2018.

[3] B. Balhan *et al.*, "Improvements to the SPS Slow Extraction for High Intensity Operation", Rep. CERN-ACC-NOTE-2019-0010, CERN, Geneva, Switzerland, 26 Mar 2018.

[4] SPS Losses and Activation Working Group (SLAWG) meeting series, CERN, Geneva, Switzerland, `https://indico.cern.ch/category/7887/`

[5] E.H.M. Heijne, "Muon Flux Measurement with Silicon Detectors in the CERN Neutrino Beams", PhD thesis, University of Amsterdam, CERN-83-06, presented on 21 Jul 1983.

[6] M. Pari *et al.*, presented at the IPAC'19, Melbourne, Australia, May 2019, paper WEPMP035, this conference.

[7] F. M. Velotti *et al.*, presented at the IPAC'19, Melbourne, Australia, May 2019, paper WEPMP034, this conference.

[8] F. M. Velotti *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, paper TUPAF035, pp. 761–764.

[9] J.P. Prieto *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, paper TUPAF050, pp. 818–821.

[10] M. A. Fraser *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, paper TUPAF054, pp. 834–837.

[11] L.S. Esposito, "First FLUKA Results of LSS2 Loss Maps", presentation at the SPS Loss and Activation Working Group meeting #26, CERN, Geneva, Switzerland, 7 Feb 2018, `https://indico.cern.ch/event/701592/`

[12] J.P. Prieto *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, paper TUPAF052, pp. 826–829.

[13] J.P. Prieto, "ZS Alignment and Loss Reduction Studies", presentation at the ABT Engineering Forum, CERN, Geneva, Switzerland, 10 Oct 2018, `https://indico.cern.ch/event/750457/`

[14] S. Hirlaender *et al.*, presented at the IPAC'19, Melbourne, Australia, May 2019, paper THPRB080, this conference.

[15] M.A. Fraser *et al.*, "Upgraded Beam Instrumentation for Slow Extraction at SPS", EDMS no. 2113420, Geneva, CERN, Switzerland, 2019.

[16] Review at the SPS Losses and Activation Working Group meeting #5, "Slow extraction loss reduction brainstorming", CERN, Geneva, Switzerland, 1 Sept. 2016, `https://indico.cern.ch/event/562757/`

[17] L. S. Stoel *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, paper TUPAF055, pp. 838–841.

[18] V. Kain *et al.*, "Resonant Slow Extraction with Constant Optics for Improved Separatrix Control at the Extraction Septum", submitted to Phys. Rev. Accel. Beams.

[19] L. S. Stoel *et al.*, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper MOPIK046, pp. 615–618.

[20] L. S. Stoel *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, paper TUPAF051, pp. 822–825.

[21] L.S. Stoel, "Low-loss resonant extraction from hadron synchrotrons in the TeV energy scale", PhD thesis, T.U. Wien, to be published.

[22] M.A. Fraser, L.S. Stoel and F.M. Velotti, "Injector MD Procedure, SPS: Separatrix Folding with Octupoles During Resonant Slow Extraction", EDMS no. 2014948, Geneva, CERN, Switzerland, 2018.

[23] L.S. Stoel *et al.*, "MD#4164: Separatrix folding with octupoles during slow extraction at SPS", Rep. CERN-ACC-NOTE-2019-0004, CERN, Geneva, Switzerland, 18 Feb 2019.

[24] L.S. Stoel *et al.*, presented at the IPAC'19, Melbourne, Australia, May 2019, paper WEPMP033, this conference.

[25] B. Goddard *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, paper TUPAF053, pp. 830–833.

[26] B. Goddard *et al.*, "Reduction of 400 GeV Slow Extraction Beam Loss with a Wire Diffuser at the CERN SPS", submitted to Phys. Rev. Accel. Beams.

[27] F. M. Velotti *et al.*, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper MOPIK050, pp. 631–634.

[28] F. M. Velotti, "Higher brightness beams from the SPS for the HL-LHC era", PhD thesis, Ecole Polytechnique de Lausanne, Rep. CERN-THESIS-2017-041, presented on 9 Mar 2017.

[29] F. M. Velotti *et al.*, presented at the IPAC'19, Melbourne, Australia, May 2019, paper THXXPLM2, this conference.

[30] M.A. Fraser, B. Goddard and F.M. Velotti, "Functional Specification for a Thin Bent Crystal Located in LSS2 for the Shadowing Tests of the ZS wires in 2018", EDMS no. 1783433, Geneva, CERN, Switzerland, 2017.

[31] L. S. Esposito *et al.*, presented at the IPAC'19, Melbourne, Australia, May 2019, paper WEPMP028, this conference.

[32] K. Brunner *et al.*, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, paper TUPAF061, pp. 862–865.

[33] D. Björkman, "Progress on the LSS2 FLUKA Model", presentation at the SPS Loss and Activation Working Group meeting #16, CERN, Geneva, Switzerland, 5 Apr. 2017, `https://indico.cern.ch/event/621754/`

[34] D. Björkman and L.S. Esposito, "Establishing a FLUKA Model for Slow Extraction in LSS2", presentation at the SPS Loss and Activation Working Group meeting #25, CERN, Geneva, Switzerland, 24 Jan. 2018, `https://indico.cern.ch/event/687186/`

[35] S. Wuyckens, "Impact of the Beam Losses on the Feedthroughs of the SPS Electrostatic Septa", presentation at the SPS Loss and Activation Working Group meeting #34, CERN, Geneva, Switzerland, 29 Aug 2018, `https://indico.cern.ch/event/748453/`

[36] D. Björkman *et al.*, presented at the IPAC'19, Melbourne, Australia, May 2019, paper WEPMP024, this conference.