MODEL AND MEASUREMENTS OF CERN-SPS SLOW EXTRACTION SPILL RE-SHAPING — THE BURST MODE SLOW EXTRACTION

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Abstract

The ENUBET (Enhanced NeUtrino BEams from kaon Tagging) Project aims at reaching a new level of precision of the short-baseline neutrino cross section measurement by using an instrumented decay tunnel. The North Area (NA) experimental facility of the CERN Super Proton Synchrotron (SPS) offers the required infrastructure for the experiment. A new slow extraction type, consisting of bursts of many consecutive millisecond spills within one macro spill, has been modeled and tested for the ENUBET Project. The burst-mode slow extraction has been tested for the first time at CERN-SPS, and MADX simulations of the process have been developed. In this paper the experimental results obtained during the test campaign are presented along with the results of the quality of the produced spill and comparing it with predictions from simulations.

INTRODUCTION

The ENUBET (Enhanced NeUtrino BEams from kaon Tagging) Project proposes to tackle the open problems in neutrino physics by developing a "monitored neutrino beam", where the initial conditions on the neutrino flux could be measured at the 1% level [1–3]. In a monitored neutrino beam the secondary hadron decay tunnel is instrumented with detector technology. In such a way the neutrino flux can be predicted by detecting the decay products of neutrino production vertices. Pile-up levels in the instrumented decay tunnel pose hard constraints on the maximum hadron flux that can be produced, making the slow resonant extraction the best option to deliver primary protons. For this reason, the development and optimization of compatible slow-extraction schemes is ongoing at the CERN-SPS, which would fulfill the ENUBET requirements in terms of spill structure and proton energy. A novel proposed extraction scheme [2] consists of the slow-extraction of several 2-10 ms pulses, at a repetition rate of 10 Hz. This particular extraction scheme, called burst-mode slow-extraction, would open the possibility of employing pulsed strong focusing devices, such as magnetic horns, for the focusing of the secondary hadrons. As shown in [3], this would increase the secondary flux by about an order of magnitude with respect to the nominal case. Moreover, the combination of a burst-extracted spill with a static focusing system could also be an option, with possible advantages in the hadron flux monitoring along the beamline and cosmic background at the neutrino detector.

BURST MODE SLOW EXTRACTION IMPLEMENTATION

The SPS slow extraction is a chromatic based, third integer resonant extraction, as detailed in [4, 5]. The horizontal tune of the machine (Q_H) is swept across a third integer resonance, extracting an intensity of about 4×10^{13} protons in 4.8 s. In order to pulse the extracted intensity, the basic idea is to reshape the demanded tune function. By defining T as the burst repetition period, the tune for nominal slow extraction in the n-th burst period can be written as $Q_\mathrm{H}^\mathrm{nom}(t+nT)$ for $t \in [0, T]$. The tune for burst mode slow extraction in the n-th burst period is obtained with the following reshaping:

$$Q_\mathrm{H}^\mathrm{nom}(t+nT) \longrightarrow \begin{cases} Q_\mathrm{H}^\mathrm{nom}\left(\frac{T}{\lambda}t+nT\right) & t \in [0,\lambda] \\ f(t+nT) & t \in [\lambda, T] \end{cases} \qquad (1)$$

where we define λ as the length of a single burst. Since the tune has to be a stricly increasing function for a continuous extaction, Eq (1) shows that particles are extracted only for $t \in [0, \lambda]$, every period n. For $t \in [\lambda, T]$ the function $f(t+nT)$ breaks the strict monotonicity, being equal or lower than the last tune value $Q_\mathrm{H}^\mathrm{nom}\big((n+1)T\big)$.

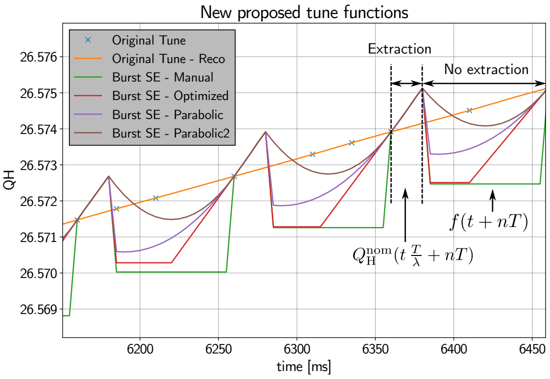

Figure 1: Proposed tune functions for burst-mode slow-extraction operation during a machine development at CERN-SPS.

Figure 1 shows the possible burst extraction tune functions produced for machine operation, superimposed to the nominal extraction tune (orange line and blue crosses), as described in Eq. (1). All the burst extraction tune functions shown in Fig. 1 are only differing in the function $f(t)$ of Eq. (1). During operation, we observed that particular shapes of $f(t)$ can significantly worsen the extracted spill due to the non-ideal response of the main power converters.

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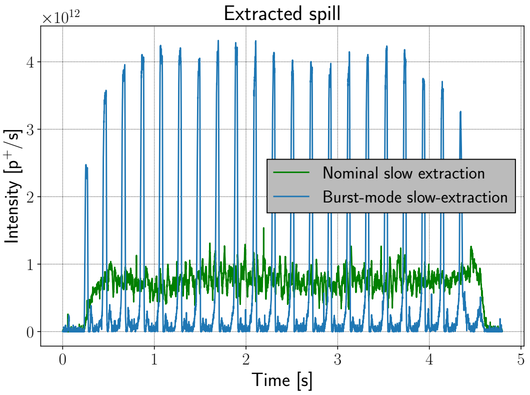

Figure 2: Secondary emission monitor measurement of the spill during a burst-mode slow-extraction machine development.

In 2018, the burst mode slow extraction was tested at the SPS: Fig. 2 shows the result of the first attempt. Also, it is possible to observe the difference between the nominal flat spill and the bursted spill. In particular, the number of extracted protons in a burst period is the same as in the flat spill case, leading to about a factor T/λ in the peak intensity between the two schemes. The approach of acting on the machine tune has proven to be particularly efficient and stable from an operational point of view. Thanks to the LSA framework [6] the tune function needed for the burst extraction can be loaded in one single operation. This opens the possibility to switch between normal and burst extraction cycle to cycle. Moreover, the peak intensity of the bursts can be adjusted within the maximum value defined by ENUBET in [2], by acting on the total circulating intensity and T/λ. No significant impact on extraction losses or remaining circulating intensity dumped at the end of the cycle was observed. An important characteristic of the burst-mode slow-extraction is the burst length λ. Possible ENUBET operation at 2 and 10 ms of burst length has been described in [2]. The parameter that has been chosen to characterize the burst length is based on the effective spill length [7], and defined as:

$$\lambda_{\text{eff}}^{n} = \frac{\left(\int_{-T/2}^{T/2} s(t+nT+t_0)\,dt\right)^2}{\int_{-T/2}^{T/2} s^2(t+nT+t_0)\,dt} \tag{2}$$

where λ_{eff}^{n} is the effective burst length of the n-th burst inside the extracted spill, $s(t)$ is the spill (i.e. extracted intensity as function of time) and t_0 is the center of the first burst in the spill. In the measurements, a systematic increase of the effective burst length with respect to the demanded one is observed; this can be amplified by shaping $f(t)$ and the nominal tune function. For example, in a typical operation, from a demanded burst length $\lambda_{\text{IN}} = 10$ ms, we observed an average effective burst length $\lambda_{\text{eff}} = 17.8 \pm 0.1$ ms. The absolute value of the obtained λ_{eff} could be decreased by manually reducing the value of λ_{IN}, but the ratio $\lambda_{\text{eff}}/\lambda_{\text{IN}}$ would increase. An iterative algorithm to be used in operation would be the ideal solution for an automatic convergence to the desired value of burst length. In particular, this solution has been implemented by upgrading the Autospill feed-forward algorithm [8] for burst extraction operation. The algorithm compares a measure of the extracted spill to a reference spill and acts on the tune function to minimize the difference. The net effect is a reduction of the demanded burst length λ_{IN}^{i} at every i-th iteration, until $\lambda_{\text{eff}} \simeq \lambda_{\text{IN}}^{0}$. In a first test, with $\lambda_{\text{IN}}^{0} = 10$ ms, the algorithm successfully optimized the effective burst length from a value of 19 ms to $\lambda_{\text{eff}} = 10.6 \pm 0.1$ ms. Such an optimization, reported in Fig. 3, took only three iterations, proving the potential of the concept.

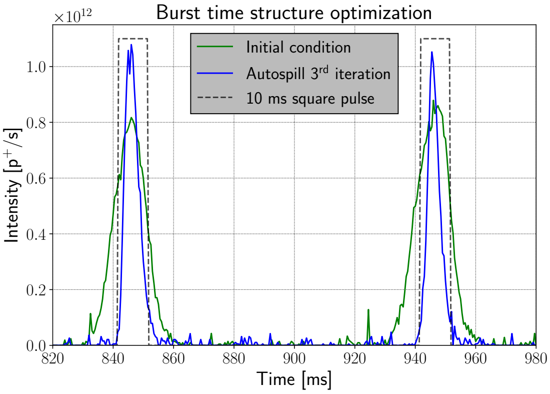

Figure 3: Successful application of the Autospill feed-forward optimization during burst extraction operation, with $\lambda_{\text{IN}}^{0} = 10$ ms. A 10 ms-long square pulse centered on the bursts (dashed black line) helps to visualize the optimization between the initial condition (green line) and the final Autospill result (blue line).

MODELING AND SIMULATION

A model of the burst-mode slow-extraction has been implemented in MADX [9]. The function $f(t)$ of Eq. (1) has been replaced by a linear symmetric "V"-shaped model, characterized by the only parameter $\min(f(t+nT))/f(\lambda+nT)$, with $t \in [\lambda, T]$. This parameter is referred to as fractional come-back depth and the notation refers to Eq (1).

The average effective burst length has then been computed at a fixed $\lambda_{\text{IN}} = 10$ ms for realistic values of fractional come-back depth. The result is shown in Fig. 4, together with the best obtained experimental value. It is important to notice that, even in simulations, λ_{eff} is larger than λ_{IN}. This proves that the higher burst length saw experimentally does not entirely come from the power converters chain, but it includes a beam dynamics component. Moreover, the dependence of the effective burst length on the fractional come-back depth is explained by the fact that the number of extracted particles is dependent on the tune speed [10].

Figure 5 shows the effective burst length ratio $\lambda_{\text{eff}}/\lambda_{\text{IN}}$ evolution as a function of the demanded λ_{IN} (from 2 to 10 ms). It is possible to observe that the experimental data (light

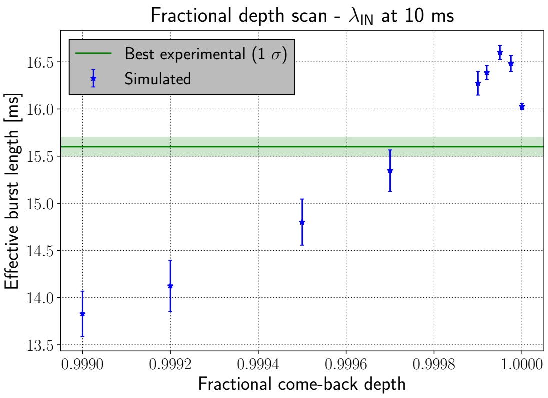

Figure 4: Average effective burst length as a function of the fractional come-back depth parameter for a fixed input burst length of 10 ms. The green line represents the best experimental result.

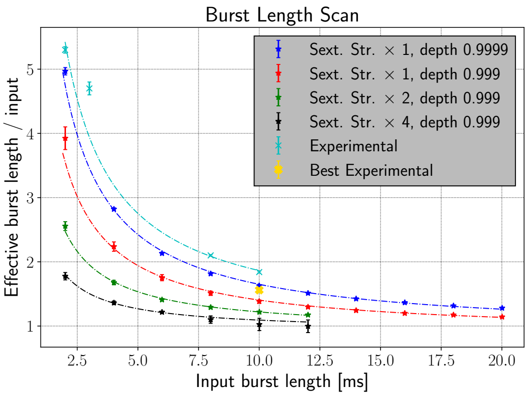

Figure 5: Ratio between effective burst length and demanded burst length, as a function of the demanded burst length.

blue) lie above the worst case depth (maximum of Fig. 4). It is believed that this effect comes from the power converters response, which worsen the overall achievable burst length (upper shift of the curve). The best experimental value was obtained using a single Autospill iteration combined with a Savitzky-Golay [11] filtering of the measured spill. Such technique reduced the non-ideal effect of the power converters, bringing the effective spill length to a value compatible with beam dynamics effects only. One explanation for the increase of $\lambda_{\text{eff}}/\lambda_{\text{IN}}$ for smaller λ_{IN} is thought to be linked to the low pass filter effect of the slow extraction process on the tune variations [12, 13]. The effect originates from the transit time in phase space for particles to leave the beam core and be extracted. Increasing the phase space velocity and reducing the transit time could be a way to reduce the low pass filter effect. In particular, near a third integer resonance, the 3-turn increase in amplitude is proportional to the sextupole strength: hence, by increasing the sextupole strength, the rate of amplitude growth increases. It can be seen from Fig. 5 that the burst length ratio is reduced down to a value of 1 for a 10 ms demanded burst length at 4 times the nominal sextupole strength in SPS.

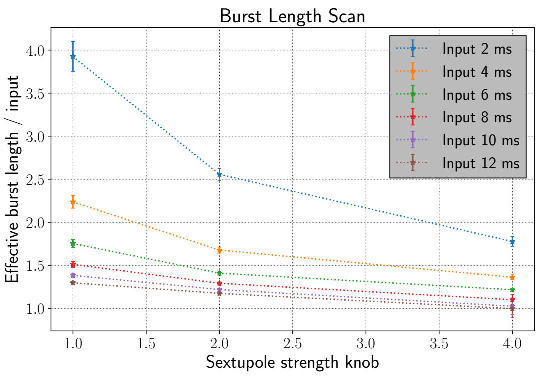

Figure 6: Simulated ratio between effective burst length and demanded burst length, for different demanded burst lengths (referred as “Input” in the legend), as a function of the sextupole strength knob.

Figure 6 shows the evolution of the simulated burst length ratios as a function of the sextupole strength knob, which is defined as the multiplicative factor between the nominal and the used sextupole strength. The maximum simulated strength is 4 times the nominal value. It can be seen that the improvement in the burst length ratios is larger the smaller the demanded burst length values.

CONCLUSION

The burst-mode slow-extraction, envisaged by the ENUBET Project for applications in monitored neutrino beams, has been successfully implemented at the CERN-SPS for the first time. No significant increase of losses or dumped intensity was shown during beam tests. The measured spill is characterized in terms of the effective burst length parameter, which was generally higher than the demanded burst length set during operation. In order to optimally control the effective burst length, an iterative feed-forward algorithm has been employed to reduce the effective burst length to the demanded value. The first tests of the algorithm proved the feasibility of the technique. Finally, to fully characterize this new type of extraction, MADX simulations have been developed. The first results show an interesting beam dynamics component in the $\lambda_{\text{eff}}/\lambda_{\text{IN}}$ increase for small λ_{IN}. It is also shown in simulation that this effect can be reduced by increasing the sextupole strength. All of these results will be further investigated in the future, both with experimental tests and more complex and efficient modeling.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the SPS operators and everyone that helped to successfully carry out our machine developments in such a busy year. Moreover, we also thank the ENUBET collaboration for making this project possible in the first place and for fruitful feedback and discussion.

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement no. 681647.

REFERENCES

[1] A. Longhin, L. Ludovici and F. Terranova, "A Novel Technique for the Measurement of the Electron Neutrino Cross Section", *Eur. Phys. J. C*, vol. 75, no. 155, 2015, `doi:10.1140/epjc/s10052-015-3378-9`

[2] A. Berra *et al.*, ENUBET Collaboration, "Enabling precise measurements of flux in accelerator neutrino beams: the ENUBET project", CERN, Geneva, Switzerland, Rep. CERN-SPSC-2016-036, Oct. 2016.

[3] F. Acerbi *et al.*, ENUBET Collaboration, "The ENUBET Project", CERN, Geneva, Switzerland, Rep. CERN-SPSC-2018-034, Oct. 2018.

[4] F. M. Velotti *et al.*, "Characterisation of the SPS slow-extraction parameters", in *Proc. IPAC'16*, Busan, Korea, June 2016, pp. 3918-3921, `doi:10.18429/JACoW-IPAC2016-THPOR055`

[5] V. Kain *et al.*, "CERN-SPS Slow Extraction Overview", presented at Slow Extraction Workshop 2017, CERN, Geneva, Switzerland, 9-11 November 2017.

[6] G. Kruk, S. Deghaye, M. Lamont, M. Misiowiec and W. Sliwinski, "LHC Software Architecture [LSA] – Evolution toward lhc beam commissioning", in *Proc. ICALEPCS'07*, Knoxville, Tennessee, USA, Oct. 2007, paper WOPA03, pp. 307-309.

[7] H. Weisberg, "Effective Spill Length Monitor", Brookhaven National Laboratory, Upton, New York, AGS Division Technical Note no. 163, Apr. 1980.

[8] V. Kain, K. Cornelis and E. Effinger, "New spill control for the slow extraction in the multi-cycling SPS", in *Proc. IPAC'16*, Busan, Korea, June 2016, `doi:10.18429/JACoW-IPAC2016-TUPMR051`

[9] MAD — Methodical Accelerator Design, `http://mad.web.cern.ch/mad/`

[10] K. Cornelis, "Momentum Cleaning in the LHC with resonant extraction", CERN, Geneva, Switzerland, LHC-PROJECT-NOTE-176, Dec. 1998.

[11] A. Savitzky and M. J. E. Golay, "Smoothing and Differentiation of Data by Simplified Least Squares Procedures", *Analytical Chemistry*, vol. 36, no. 8, pp 1627-1639, 1964, `doi:10.1021/ac60214a047`

[12] F. M. Velotti *et al.*, "Observations of SPS Slow-Extracted Spill Quality Degradation and Possible Improvements", in *Proc. IPAC'18*, Vancouver, Canada, Apr. 2018, `doi:10.18429/JACoW-IPAC2018-TUPAF035`

[13] J. Prieto *et al.*, "Beam Dynamics Simulations of the Effect of Power Converter Ripple on Slow Extraction at the CERN SPS", in *Proc. IPAC'18*, Vancouver, Canada, Apr. 2018, `doi:10.18429/JACoW-IPAC2018-TUPAF050`