NEW SPILL CONTROL FOR THE SLOW EXTRACTION IN THE MULTI-CYCLING SPS

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Abstract

The flux of particles slow extracted with the 1/3 integer resonance from the Super Proton Synchrotron at CERN was previously controlled with a servo-spill feed-back system which acted on the horizontal tune such as to keep the spill rate as constant as possible during the whole extraction time. The current in two servo-quadrupoles was modulated as a function of the difference between the measured and the desired spill rate. With servo quadrupoles at a single location in the SPS ring and the SPS in multi-cycling mode, the trajectory of the slow extracted beam was seen to change from cycle to cycle depending on the current applied by the servo feed-back. Hence this system was replaced by a feed-forward tune correction using the main SPS quadrupoles. In this way the spill control can now be guaranteed without changing the trajectory of the extracted beam. This paper presents the algorithm and implementation in the control system and summarizes the advantages of the new approach. The obtained spill characteristics will be discussed. The technique implemented for the additional reduction of the 50 Hz noise on the spill structure will also be briefly outlined.

INTRODUCTION

The third order resonant extraction from long straight section 2 (LSS2) at the Super Proton Synchrotron (SPS) at CERN serves the fixed target experiments in the SPS North Area. The SPS layout with the different extraction zones, transfer lines and experimental areas is shown in Fig. 1. The beam is slow extracted from LSS2 into the transfer line TT20 where it is split to finally impact on three targets T2, T4 and T6 where the secondary beam is generated. The LHC transfer line from the SPS are also shown in Fig. 1.

A set of sextupoles are used at the top energy of 400 GeV in the SPS to create a stable area in the radial phase space of the beam. Initially it is larger than the area occupied by the beam. The machine tune is gradually moved towards $Q_h = 26\,^2/_3$ by adjusting the main quadrupole circuits QD and QF which leads to a reduction of the stable phase space area towards zero. The particles with phase space coordinates outside the stable region move away from it along the separatrices until they enter into the field of the electrostatic septum (ZS) which deflects them into the extraction channel consisting of eight septum magnets. A horizontal orbit bump is used in addition to bring the circulating beam close to the ZS and control the horizontal size of the extracted beam.

For an ideal spill, the rate of extracted particles dN/dt should remain constant. In the past the intensity signal from the beam extracted to the North Area transfer lines was compared to a reference value and used in a feed-back loop with the dedicated servo-quadrupole system consisting of 4 short QMS quadrupoles installed in cell 116 [1]. The servo quadupole feed-back was in use until end of 2014.

SERVO-SPILL SYSTEM LIMITATION

In 2014 the SPS started up in multi-cycling mode and a new power converter control system to dynamically switch into and out of economy cycles had been implemented. Several fixed target cycles had to be used in the so-called supercycle of the SPS preceded by different magnetic cycles. This resulted in changing beam parameters and hence different servo-quadrupole excitation during the slow extraction from cycle to cycle. The different quadrupole excitation impacted the horizontal steering in the TT20 extraction transfer line and hence on the targets. An example for the fluctuations of the parameter *symmetry* on target T4, which represents the steering quality [2], is shown in Fig. 3. It should be at least 80 % and stable over time.

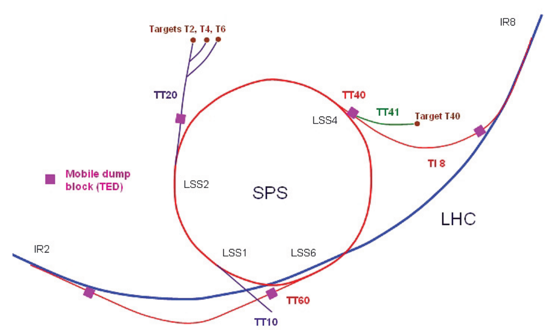

Figure 1: Layout of the SPS and its transfer lines. Several extraction zones are installed in the SPS long straight sections. LSS2 is used for the third order resonant extraction to the North Area behind the targets T2, T4 and T6.

SPILL CORRECTION WITH FEED-FORWARD

For the 2015 start-up a new concept of spill correction was implemented in the SPS control system in the form of the *Autospill* application using a feed-forward algorithm implemented in Java. Here the tune is adjusted directly through the main quadrupoles all around the SPS. The servo spill feed-back was disconnected due to the large trajectory variations in TT20.

With the new method the tune adjustment is based on the intensity measured by the ring beam current transformers instead of the extracted intensity measured in TT20. For the extracted intensity dN/dt to be constant, the ring intensity needs to decay linearly. No absolute reference for dN/dt is

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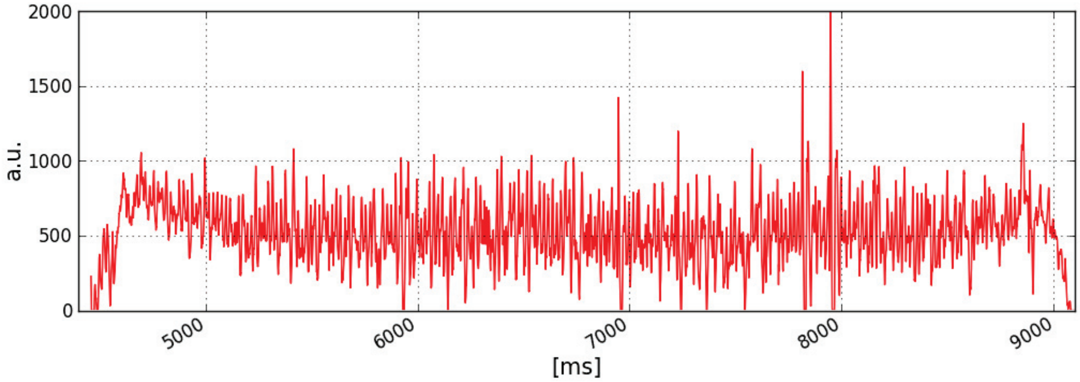

Figure 2: The evolution of a slow extracted spill recorded on July 31, 2015.

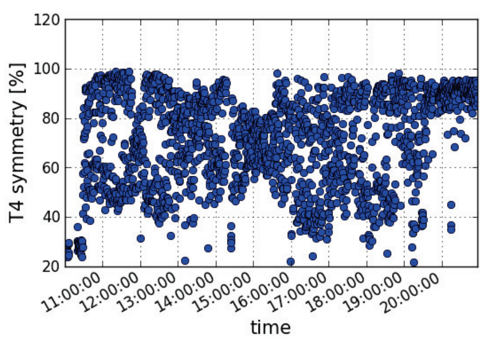

Figure 3: Servo quadrupole induced symmetry variations on North Area target T4. December 1, 2014.

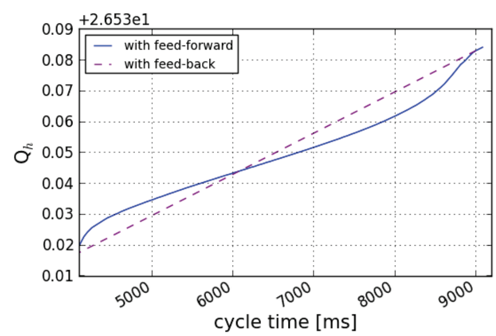

Figure 4: Programmed horizontal tune function along the extraction flattop with feed-forward tune correction (blue) and with feed-back (dashed purple line).

defined in the algorithm. The optimum extracted intensity rate is defined by the ring intensity at the start of the slow extraction and the fact that the spill should last for the whole cycle flattop of roughly 5 s.

The extracted intensity rate is proportional to the tune change

$$\frac{dN}{dt} \propto \frac{dQ_h}{dt} \tag{1}$$

The extracted intensity rate is sampled along the extraction flattop and translated into a required extracted intensity rate change which in turn corresponds to the required $\dot{Q}_h$ change. The programmed high level horizontal tune function is then re-calculated according to the required $\dot{Q}_h$ changes. The LHC based control system of the SPS then takes care of defining the required QF and QD currents from this function according to the ring optics [3]. Fig. 4 shows an example of the horizontal tune function after *Autospill* correction. The dashed line indicates the programmed tune function before the Autospill was available and where the constant extracted intensity was guaranteed by the servo quadrupoles.

In 2015 the entire proton fixed target run was run with tune feed-forward and the stability of the steering in the transfer lines much improved. An example of the evolution of the symmetry on T4 with feed-forward on the main quadrupoles is shown in Fig. 5. The symmetry fluctuations shot-to-shot are typically well within 5 %.

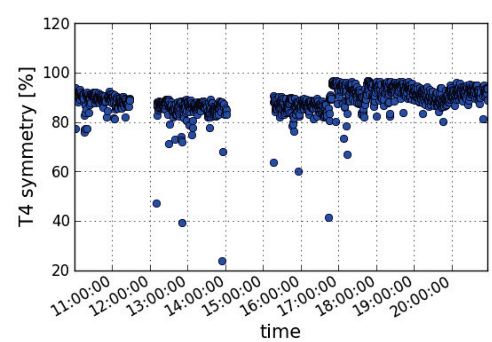

Figure 5: Symmetry variations on T4 with feed-forward on the main quadrupole tune function. October 1, 2015.

SPILL QUALITY

Fig. 2 shows the evolution of the extracted intensity over a slow extraction cycle measured with a Secondary Emission grid in the transfer line TT20. The extracted intensity varies in this particular case by about 30 %. A few isolated intensity spikes are apparent. These have been correlated with random current glitches of the QF circuit. These current glitches can be even more severe than those during the slow extraction of Fig. 2. An example is shown in Fig. 6 where the measured current and downloaded reference current of the QF circuit are displayed during a slow extraction cycle in March 2016. For current glitches of this extent, a big part of the circulating intensity is extracted rapidly causing even saturation or trips of detectors. The origin of the QF glitches is still unknown.

The remaining fluctuations are due to the 50 Hz and higher frequency ripples of the SPS power supplies. For a typical tune change rate of $\dot{Q} = 0.01\ s^{-1}$, a 50 Hz modulation amplitude of the tune of 3×10^{-6} is sufficient to generate 10 % intensity modulations. The FFT of the spill of Fig. 2 is shown in Fig. 7. 50 Hz and higher harmonics are clearly visible.

The servo-quadrupole system was equipped with a 50 Hz modulation with phase and amplitude adjustable to the mains on top of its current. In the middle of the run in 2015 the possibility to inject 50 Hz and higher tune modulation through the servo system was revived. Initially the parameters were set manually as in previous years. Later on a measurement of the injected 50 Hz signal was made available in the control room to deterministically find the correct phase with respect to the 50 Hz modulation of the spill. Currently the amplitude setting still requires a manual scan.

A good correction of the 50 Hz lines can be achieved with this system. (The 50 Hz noise was not well corrected for the spill in Fig. 2). Unfortunately the required phase and amplitude drift over less than 24 h. The 50 Hz optimisation scan has to be periodically repeated.

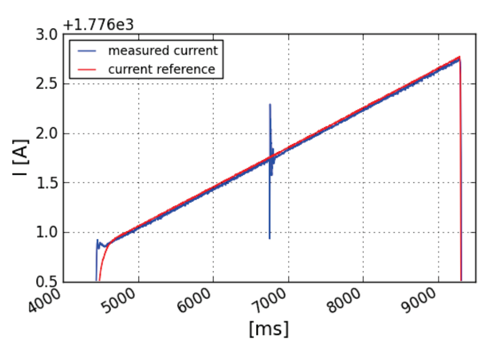

Figure 6: Current of the main quadrupole circuit QF in the SPS in blue and reference on the flattop of the fixed target cycle. In the middle of the flattop a current glitch occurs with an amplitude of about ± 0.75 A.

LIMITATIONS OF FEED-FORWARD METHOD FOR SPILL CORRECTION

The supercycle composition dependence of beam parameters in the SPS is also problematic for the feed-forward spill correction approach. If the supercycle composition is modified or some of the cycles in the supercycle are played in economy mode where the magnets are not ramped to top field, the slow extracted intensity rate changes. The feed-forward tune correction is then not adequate anymore and

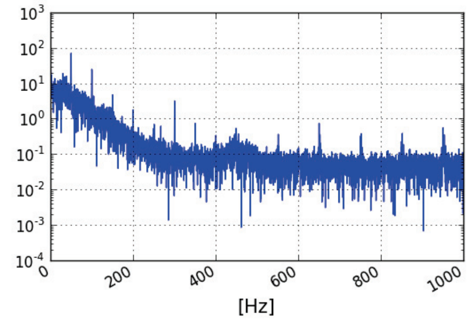

Figure 7: FFT of the spill in Fig. 2.

has to be re-calculated with the *Autospill* application. If however the supercycle configuration changes continuously like for example during LHC filling, extended periods with insufficiently adjusted spill can be expected.

If the effects from changing supercycles cannot be compensated in the future, a possible improvement of the spill correction without losing the stability of the steering could be to re-activate the servo system and use the feed-back to only correct dynamic changes. The feed-forward would define the main tune change rate.

SUMMARY

With the servo quadrupole feed-back system to control the spill rate for the slow extraction to the SPS North Area, the trajectory of the beam in the transfer line was changing from cycle to cycle depending on the current applied by the servo feed-back. This system was replaced by a feed-forward tune correction algorithm using the main SPS quadrupoles in 2015. Instead of measuring the extracted intensity, the ring intensity decay rate is measured and adjusted by modifying the tune change rate. It was shown that the feed-forward can adequately control the spill while keeping the trajectory constant. The servo quadrupole system is still used to inject 50 Hz and higher frequency tune modulations to compensate the 50 Hz intensity modulation of the spill.

A limitation for the feed-forward approach is coming from the supercycle dependence of the beam parameters and dynamically changing supercycle configurations, which are not followed automatically. Solutions will have to be found to either compensate the effects from changing supercyles or to upgrade the current tools to also work under dynamically changing conditions.

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