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SPS FIXED TARGET SPILL QUALITY IMPROVEMENTS IN THE LONGITUDINAL PLANE

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Abstract

The SPS proton fixed target beams are spilled via a third integer resonant extraction, for which high momentum spread is beneficial. To increase the momentum spread prior to the slow extraction, the bunches are stretched at the unstable phase by inverting the sign of the RF voltage. The RF phase is then flipped back, and the voltage is turned off when the bunch distribution is rotated to the maximum momentum spread. The past production scheme additionally relied on uncontrolled longitudinal blow-up of the unstable beam during the acceleration ramp. After the major upgrade of the main RF system and a successful impedance reduction campaign, the spill quality was significantly compromised. This contribution summarizes the efforts to recover, and improve, the spill quality. The use of the fourth harmonic RF system and controlled longitudinal emittance blow-up are used for beam stabilization along the ramp. Moreover, RF counter phasing is applied during the first part of the de-bunching to profit from the cavity impedance reduction of the feedback systems.

INTRODUCTION

The CERN Super Proton Synchrotron (SPS) provides beam to a rich fixed target physics programme in the SPS North Area (NA). About ten elevenths of the SPS circumference are populated via two transfers at 14 GeV/c from the Proton Synchrotron (PS), accelerated to 400 GeV/c, and then slowly extracted over a 4.8 seconds long flat top (i.e. $2 \cdot 10^5$ turns). A resonant multi-turn extraction is applied: the number of betatron oscillations per turn is adjusted close to the 3rd order integer resonance allowing to drive particles slowly across the blades of the septa, and thus into the transfer line towards the experimental area.

The experiments [1] need a quasi-continuous flux of particles over the length of the spill, i.e. the rate of the extracted particles should remain constant along the extraction flattop. Any strong modulation at a frequency in the extracted beam can impair the experimental data quality. Notable examples are the 50 Hz and 100 Hz ripples due to noise in the power supplies of the main dipoles and quadrupoles, and a possible residual 200 MHz component due to the main Radio-Frequency (RF) system.

Until 2021, the SPS cycle used to rely on uncontrolled longitudinal blow-up during the ramp (beam instability), to further increase the longitudinal emittance and stabilize the beam. A phase jump to the unstable phase, and back, at the start of the flat top, allowed to increase the momentum spread $\Delta p/p$, which is beneficial to the quality of the spill as it reduces the impact of power supply ripples. Lastly, the RF was turned off after the phase jump to allow the beam to debunch, removing the 200 MHz structure.

During the 2019-2020 stop (i.e. “Long Shutdown 2”, LS2) the SPS was upgraded according to the LHC Injector Upgrade project (LIU, [2]). The LIU SPS upgrades included the addition of two power plants based on transistor amplifiers, a re-arrangement of the 200 MHz accelerating structures to reduce the beam loading effects, new digital Low Level RF controls (LLRF, [3]). A longitudinal impedance reduction campaign also took place to increase the instability thresholds in particular for the LHC beams [4]. Vacuum flanges with a strong resonant peak at $f = 1.4$ GHz were identified, and then shielded during LS2, to reduce their beam coupling impedance. In 2021, a measurement of the debunching with long bunches at injection confirmed that the 1.4 GHz peak is suppressed, and that the main remaining impedance source is at 200 MHz, i.e. the main RF system frequency.

When beam operation restarted in 2021, though, the spill quality was compromised. The experiments, in particular NA62 [5], observed a bump and flares in the particle flux at the start of the spill, which rendered the collected data quality unacceptable due to detector saturation and trips [6].

This paper summarises the efforts carried out in 2022 to improve the spill quality. The higher harmonic 800 MHz system and Controlled Longitudinal Emittance Blow-Up (CLEBU) are applied for beam stabilization, replacing the uncontrolled blow-up (insufficient after the impedance reduction campaign). Instead of turning the RF immediately off at the start of extraction, the RF is maintained on during the first part of debunching to profit from the LLRF one-turn delay feedback for its impedance reduction capability. The RF is then turned off, after the initial transients have passed, to avoid issues with a residual 200 MHz structure and possible trips, as well as to save power.

LONGITUDINAL BEAM STABILIZATION DURING ACCELERATION

The use of the 800 MHz RF system and CLEBU is the foundation for beam stability of the proton LHC beams in the SPS. Similar techniques were never required for the fixed target beams, even though the use of the 800 MHz proved beneficial already in 1997 [7, 8]. After the LS2 impedance reduction campaign, the uncontrolled emittance blow-up became insufficient, and the use of the 800 MHz RF system combined with CLEBU was pursued in operation in early 2022 for beam stabilization and spill quality recovery. This resulted in a controlled preparation of the beam, which opens the way to future intensity increases.

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The 800 MHz RF system increases the synchrotron frequency spread in the bunch, thus Landau damping. It is used in bunch shortening mode, i.e. with a 180 degree shift between the two RF systems, and it is active from about 100 turns after transition.

During the CLEBU, starting at about 10k turns after transition, bandwidth limited phase noise is injected into the beam phase loop. This technique allows to target the bunch core only by choosing the noise bandwidth. This is necessary due to the limited bucket area available at that time in the cycle. Experimentally, its amplitude was adjusted to flatten the peak detected beam signal evolution during the ramp (i.e. constant bunch length). Figure 1 illustrates the typical peak detected signal in the case of the beam getting unstable without 800 MHz RF and CLEBU. With 800 MHz and CLEBU, the beam remains longitudinally stable throughout the entire cycle (Fig. 2).

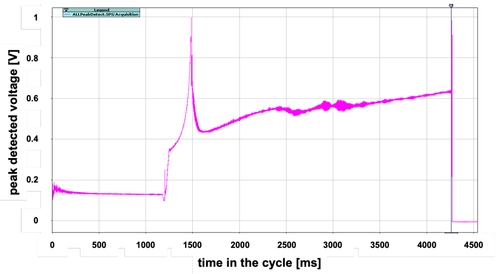

Figure 1: Peak detected signal through the cycle (no 800 MHz and no CLEBU): 1200 ms flat bottom, acceleration through transition, instability in the middle of the cycle.

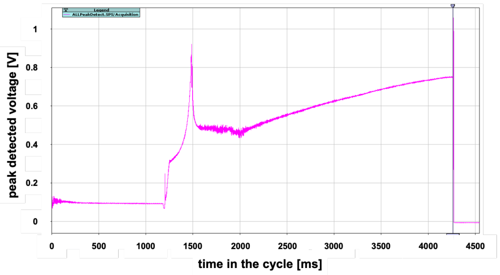

Figure 2: Peak detected signal through the cycle with 800 MHz and CLEBU shortly after transition (approx. 1500–2000 ms). The beam is longitudinally stable at all times.

Stretching the bunch at the unstable fixed point and subsequent rotation [9] has been operational both before and after LS2 to achieve a flatter and wider momentum distribution, $\Delta p/p$, for the slow extraction. In combination with CLEBU, the momentum spread $\Delta p/p$ could be increased by about 50% (Fig. 3), resulting also in a flatter $\Delta p/p$ profile, which is beneficial for the spill quality.

The setting stability proved to be good during the 2022 run: the initial beam optimization was done with $1.4 \cdot 10^{13}$ protons accelerated (at the start of the run), and the same settings were in use until the end of the year, up to $4 \cdot 10^{13}$ protons per pulse. While the momentum distribution was of sufficient quality throughout the entire run, at the last intensity step the beam became mildly unstable in the early part of the ramp. This will be subject of future studies.

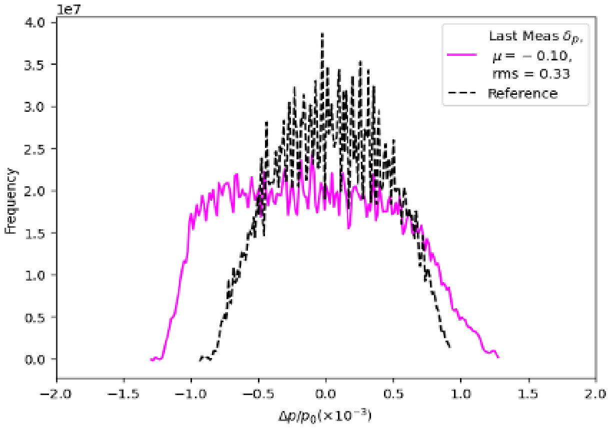

Figure 3: $\Delta p/p$ profile [10]: before (reference, black) and after (magenta, with CLEBU and optimised phase jump).

SPILL QUALITY IMPROVEMENT

Counterphasing for Impedance Reduction

For the fixed target beam at the flat top, the beam is debunched, targeting a uniform spill. Due to the LS2 impedance reduction campaign though, even though reduced with respect to before LS2, the 200 MHz are now the main source of profile modulation during debunching.

Up to 2021, debunching was achieved by turning the RF off. The RF was switched off by disabling its drive signal, hence the bare cavity impedance remained present. In 2022, this was done by actively requesting a total voltage $V_{\mathrm{RF}} = 0$, to profit from the LLRF One-Turn Delay Feedback impedance reduction capability.

The total voltage V_{RF} is the vector sum of the voltages from the six accelerating structures (with amplitudes V_{i} and phases ϕ_{i}, for $i = 1 \ldots 6$). Voltage and phase of each 200 MHz accelerating structure are regulated by a dedicated instance of the LLRF cavity controller. Due to non-linearities in the power plants, the cavity controller cannot regulate the individual cavity to zero, but the minimum is $V_{\mathrm{min}} = 500$ kV. To achieve a total voltage $V_{\mathrm{RF}} < 6 \cdot V_{\mathrm{min}}$, the accelerating structures are counterphased: the amplitudes are kept at $V_{\mathrm{i}} = V_{\mathrm{min}}$, and the phases ϕ_{i} are adjusted to achieve the desired value for the vector sum.

With counterphasing operational, the spill was already significantly improved, with the bump and flares removed, but the experiments, then, brought forward complaints about a too strong 200 MHz component in the slow extraction.

Indeed, as the total voltage is the vector sum of six structures, any imprecision on V_{i} and ϕ_{i} will cause V_{RF} to be different from zero, i.e. small buckets will capture a small fraction of the beam, and result in a spill modulation at 200 MHz.

A beam-based technique for voltage measurement, based on tomographic reconstructions, was recently applied at the SPS, and achieves unprecedented precision [11]. A single bunch of small intensity and emittance is captured with one travelling wave structure at a time. The measured oscillations are compared to tracking simulations to find the pair (V_i, ϕ_i) that best describes the motion, over two to four synchrotron periods. This procedure allows quantifying the errors on V_i and ϕ_i between the setpoint and the applied voltage. While the phases ϕ_i proved to be accurate to below 1°, the errors in the amplitudes were at most 5% in 2022: while this is an excellent result for the LLRF and the RF power calibration, the errors resulted in a residual total voltage of several tens of kV.

The errors on the voltage amplitudes were then used to pre-correct the voltage setpoints. Once implemented, the residual 200 MHz structure became negligible, to the satisfaction of the experiments (see Fig. 4). The correction of the phase errors did not lead to a measurable improvement.

Delayed RF Off

Nevertheless, disabling the RF drive signal has several advantages: no residual 200 MHz structure during the spill, no dependence on long term drifts, e.g. of the voltage calibration, and a cheaper electricity bill. Additionally, and more importantly, single cavity trips are disruptive to the spill quality with counterphasing, as one trip leaves other travelling wave structures unbalanced, and consequently a residual total voltage, different from zero, acts on the beam.

Because of these considerations, the active $V_\mathrm{RF} = 0$ with counterphasing is only applied during in the first part of the debunching, to control the transients, when the 200 MHz component of the beam is still strong, and to then switch the RF off until the end of the cycle (i.e. “delayed” RF off).

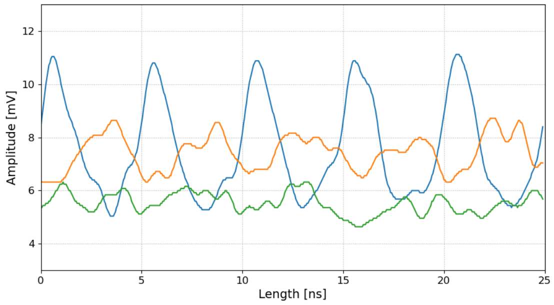

Figure 4: Longitudinal beam profiles from a wideband wall-current monitor illustrate the measured 200 MHz structure in the middle of the spill (at 2.4 s): before voltage calibration corrections blue), after voltage calibration corrections (orange), with delayed RF off (green).

The time for the RF to be turned off was scanned, and feedback from the NA62 experiment indicated that about 400 ms after the start of the spill were sufficient, as the transients had reduced to an acceptable level.

Figure 5 compares the hit occupancy in one station of the beam spectrometer (GTK) of NA62 for the years 2018 (i.e. pre-LS2), 2021, and 2022. The 1 s timestamp indicates the start of the spill. While 2018 and 2021 show excess hits for the first few hundreds ms, their number is flat in 2022. Indeed, the initial 2021 peak is higher and wider than the one in 2018, which indicates the degradation of the data collection conditions between the two years, while the spill structure in 2022 allows the data collection to extend up to the start of extraction. These results were confirmed also by other NA62 subdetectors, e.g the Muon Veto Detector (MUV3) and the dowstream spectrometer (STRAW), and by other NA experiments, e.g. COMPASS.

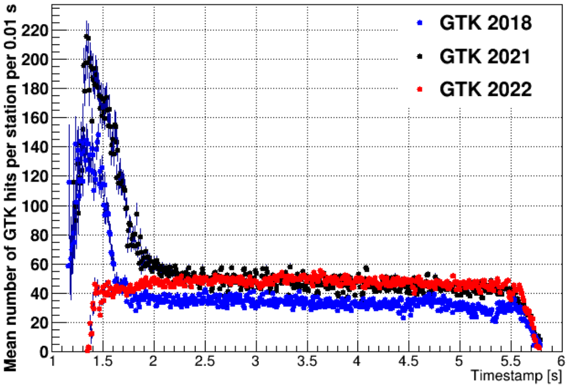

Figure 5: Comparison of 3 spills as observed by NA62. Abundant rates at the start of the spill (1-2 s) were problematic in 2018 and 2021, and not present anymore in 2022.

CONCLUSIONS AND FUTURE WORK

Many changes and improvements were made operational for the SPS proton fixed target beam in 2022. The beam is now stabilized by the use of the 800 MHz RF system and CLEBU, additionally achieving an improved $\Delta p/p$ distribution. The spill quality issues observed in 2021 are now solved, and the spill has an unprecedented quality in the longitudinal plane. The improvements are based on the use of counterphasing for a controlled zero V_RF, voltage errors pre-corrections to reduce the residual RF voltage, and a delayed RF off so not to be affected by possible cavity trips. These studies were prepared during beam commissioning and machine developments, and the final fine tuning could take place in parallel to physics, taking advantage of feedback from the experiments.

While the current setup provided sufficient beam quality up to intensities of $4 \cdot 10^{13}$ p, further studies would be required to guarantee beam stability up to those intensities. An automation of the online bunch length calculations is moreover being developed to improve the observables e.g. for the setup of the CLEBU.

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