CHARACTERISATION OF THE SPS SLOW-EXTRACTION PARAMETERS

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Abstract

The Super Proton Synchrotron (SPS) is the last accelerator in the Large Hadron Collider (LHC) injector chain but its main users are the fixed-target experiments located in the North Area (NA). The beams, which are among the most intense circulating in the SPS, are extracted to the NA over several thousands of turns by exploiting a third-integer resonant extraction. The unavoidable losses intrinsic to such an extraction makes its optimisation one of the main priorities for operation, to reduce beam induced activation of the machine. The settings of the extraction systems, together with the tune sweep speed and the beam characteristics (momentum spread, emittance, etc.) are the parameters that can be controlled for spill and loss optimisation. In this paper, the contribution of these parameters to the slow-extraction spill quality are investigated through tracking simulations. The simulation model is compared with beam measurements and optimisations suggested.

INTRODUCTION

The SPS is used to supply beams to the LHC, to the North Area, to the AWAKE [1] experiment and to the HiRadMat experimental area. It provides 450 GeV beam to the LHC thanks to the two fast extraction systems installed in the Long Straight Section (LSS) 4 and LSS6. The extraction system in LSS4 and LSS6 are also used to deliver beam to AWAKE and HiRadMat, respectively. The NA is connected to the SPS via TT20, a transfer line branching off from the SPS LSS2. At the end of TT20, the extracted beam from the SPS is split in three to deliver beam to three different targets. This experimental area hosts a wide range of test beam facilities and different fixed target experiments, e.g. North Area 62 [2], COMPASS [3], etc. The beam requirements from fixed target experiments are usually high integrated intensity (more precisely maximum spill duty factor [4]) on target. This translates in the need to use slow extraction. The LSS2 is equipped with an electrostatic septum (ZS), and two magnetic septa (MST and MSE) to exploit the horizontal one-third integer resonance to extract 400 GeV up to 4×10^{13} protons per spill from the SPS.

The slow resonant extraction is a process that permits the extraction of a constant flux of particles from a synchrotron over several thousands turns. In the SPS, the nominal spill duration is 4.8 s, which corresponds to 2×10^6 turns. This is obtained with the use of the three septa, ZS, MST and MSE, and four extraction sextupoles with constant nominal integrated strength of $k_2 = -0.12\,\mathrm{m}^{-3}$. The horizontal chromaticity is trimmed to $\xi_x = -1$ and the momentum spread is increased to enhance the beam tune spread. The particle amplitude oscillations are then driven unstable by pushing the tune towards the resonant condition $3\nu_x = n$, where ν_x is the horizontal betatron tune and n is integer. The quadrupole strength is swept through the tune spread of the beam during the length of the spill and the rate of the sweep is adjusted to guarantee a constant intensity of the extracted beam [5]. The SPS nominal tunes for the FT beam are $\nu_x = 26.66$ and $\nu_y = 26.58$, for the horizontal and vertical plane respectively. As the horizontal tune is varied between $\nu_x(1 + \xi_x\delta_{\max})$ and $\nu_x(1 + \xi_x\delta_{\min})$, particles with different momenta are extracted as function of time.

In order to avoid losses elsewhere in the machine, and of course to extract from the LSS2 extraction channel, the ZS is made the machine horizontal aperture limitation with the introduction of a closed orbit magnetic bump. Five bumpers are used to approach the circulating beam to the ZS. The maximum orbit excursion, $x_{CO} = 48$ mm, due to such a bump is reached at the focusing quadrupole just upstream of the ZS. Particles reaching the ZS upstream position with sufficient oscillation amplitude to enter the electric field region are deflected into the extraction channel (Fig. 1). The additional deflection needed to enter the quadrupole coil window, which represents the beginning of TT20, is provided by the MST and MSE.

The slow extraction process involves the control of many machine parameters, such as bump amplitude, tune sweep, chromaticity, momentum spread, etc. Each of these contribute to the efficiency and quality of the extraction. In this paper, some of the main SPS slow extraction parameters are evaluated and reference measurements and simulations are presented.

ENHANCEMENT OF MOMENTUM SPREAD

The SPS resonant slow extraction is based on the beam momentum distribution. To provide the required spill duration with as uniform as possible spill intensity rate, a so-called *RF gymnastic* is performed. The SPS RF gymnastic is a kind of RF manipulation that theoretically should uniformly distribute the particles momenta filling the whole RF bucket. After reaching the extraction energy of 400 GeV, the RF gymnastics starts. This manipulation comprises the following steps:

- the RF phase is moved to an unstable one, i.e. $\Delta\phi_s = \pi$, and kept constant for 0.3 ms;
- the phase is moved back to the nominal one for 2.25 ms;
- all RF cavity voltages are set to zero.

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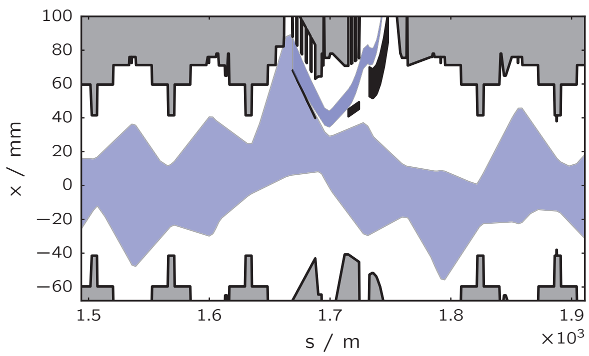

Figure 1: Envelope of the circulating and extracted beam during the SPS slow extraction. In blue, the extrema of the trajectories of the last three turns for a particle with maximum amplitude at the ZS is shown. No tolerances have been included and a spiral step of 20 mm at the ZS was assumed.

After the RF gymnastic the beam is is allowed to de-bunch to reduce any high frequency intensity modulation components in the spill (200 MHz).

Due to the SPS slow extraction nature, control and knowledge of the beam momentum spread is fundamental for the optimisation of the extraction. To measure the beam momentum spread, a Schottky pick-up [6] was used. Such a pick-up outputs the revolution frequency distribution of the beam. The momentum spread is related to the frequency spread by:

$$\delta_p \equiv \frac{\Delta p}{p_0} = \eta^{-1}\frac{\Delta f}{f_0}, \tag{1}$$

with δ_p being the momentum spread, η the slip-factor and $\Delta f/f_0$ the frequency spread. The slip-factor η is then calculated as:

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \tag{2}$$

where γ is the Lorentz factor and γ_t is the gamma transition which is estimated from the optics. In Fig. 2 the measurements of the momentum spread distribution before (green dashed line) and after (red dashed line) the RF gymnastic are shown.

A model of the SPS slow extraction and the RF gymnastic has been developed using MADX [7]. In this model, no intensity dependent effects are taken into account. Using the measured momentum spread distribution as input, the resulting distribution after the RF gymnastic is shown in Fig. 2 as red solid line. A similar trend of the evolution of the momentum distribution between measurements and simulations is observed. The discrepancy originates from the relatively long acquisition time of the network analyser used to measure the frequency range of interest. Dedicated measurements are planned to measure the momentum distribution at the end of the acceleration ramp with no RF gymnastic.

In Fig. 3 the measured momentum spread distribution almost at the end of the spill is shown. It is interesting to notice that a significant part of the negative δ_p distribution is left behind. This might be caused by the non-optimised choice of the starting point of the tune sweep when measurements were carried out. To be re-checked and possibly optimised during the 2016 physics run.

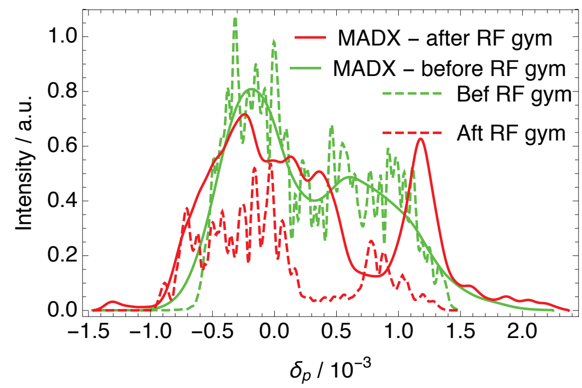

Figure 2: Momentum distribution before (green) and after (red) the RF manipulation called RF gymnastic. The measurements results are drawn in dashed lines. MADX tracking results are plotted in solid lines.

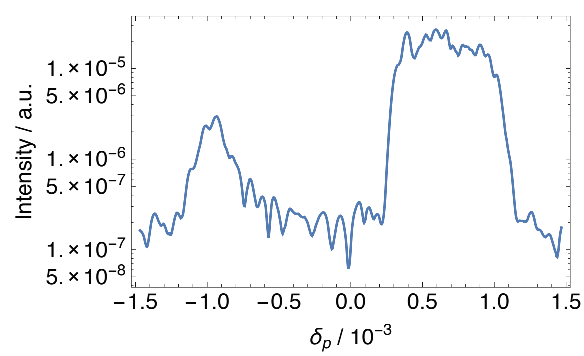

Figure 3: Measurements of the momentum spread distribution during the slow extraction.

BUMP AMPLITUDE VARIATION

The spiral step is defined as the amplitude growth in three turns for a particle with tune exactly on resonance and initial amplitude equal to the electrostatic septum wire transverse position. It can be written as:

$$\Delta X_{ZS} = \frac{3}{4}|S|\frac{X_{ZS}^2}{\cos\theta}, \tag{3}$$

where S is the normalised sextupole strength accounting for all machine sextupoles, X_{ZS} is the normalised horizontal amplitude at the ZS and θ is the angle between the extraction separatrix and the horizontal axis in normalised phase space [8]. By varying the bump amplitude, the distance between the beam centre and the electrostatic septum is changed. Hence, the spiral step can be changed by scaling the bump, as shown in Fig. 4. Reducing the bump amplitude increases the spiral step, as expected from (3). In Fig. 4 a very good

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agreement between measurements and simulations is shown, when accounting for a bump amplitude 8 % bigger than ideally calculated. This is most likely the non-zero orbit in the extraction region. From the measurements, a closed orbit of about 3.5 mm at the ZS is estimated to account for the difference with simulations.

In the last years, non-negligible variation of the SPS closed orbit has been observed for LHC beams [9] and it is believed that this could be the case also for FT beams. The beam during slow extraction is debunched, hence the SPS orbit cannot be measured with the available instrumentation. A periodic measurement of the spiral step could give information regarding the actual distance between the beam centre and the ZS wires. This information can be used to understand if the observed losses during extraction are linked to variations in the CO because the beam density of the sepratrix changes rapidly with the distance from the centre.

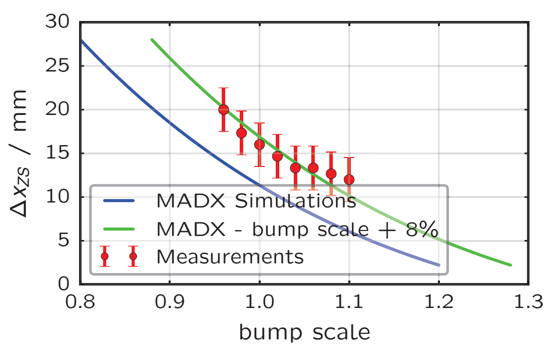

Figure 4: Evolution of the spiral step as function of the bump amplitude. In blue is plotted the spiral step as would evolve in case of perfectly ideal machine. In red dots are the measurements recorded during 2016 slow extraction commissioning. In green, the case with a bump 8 % larger than theoretically estimated is shown.

EXTRACTED BEAM PROFILE

The MADX model developed has been tuned with measured machine parameters such as chromaticity, momentum spread, spiral step, etc. To assess the quality of the model and hence to be able to compare it with measurements, tracking simulations of the whole slow extraction process were done. An initial Gaussian distribution was tracked through the RF gymnastic process. The RF cavities have been switched off and the slow extraction started. The distribution obtained at the upstream end of the ZS (Fig. 5) was tracked through the septa to finally reach TT20. The beam profile at the first grid in TT20 has been extracted and compared with the measurements (Fig. 6). A very close agreement between measurements and simulations is shown. The main difference is in the positive side of the horizontal profile. In simulations, the ZS has a sharp edge and no scattering of primary protons in the wires is considered. This is clearly not realistic, as shown in the comparison with the measurements. Such scattered particles are difficult to transport to the targets and can be source of beam losses in TT20. The tracking results are in very good agreement with the available profile measurements. The introduction of the scattering of primary protons in the ZS will be also implemented.

The comparison of measurements and simulations of the beam profiles in TT20 will be used to evaluate the optics chosen. Also, due to the availability of multiple grids and independently powered quadrupoles, a transverse phase-space tomography reconstruction will be attempted.

For this simulation, the vertical normalised emittance used was $\epsilon_y^N = 5.2$ mm mrad. This is smaller than usually obtained at high intensity.

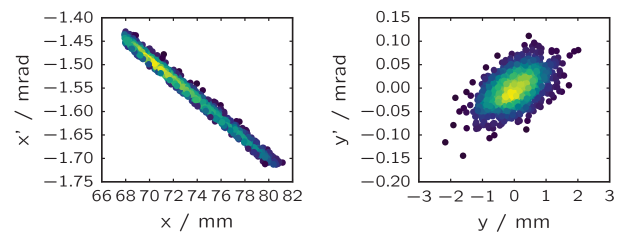

Figure 5: Horizontal (left) and vertical (right) simulated transverse phase space at the entrance of ZS at the end of the slow extraction. This has been obtained with a bump amplitude of 94 % the nominal.

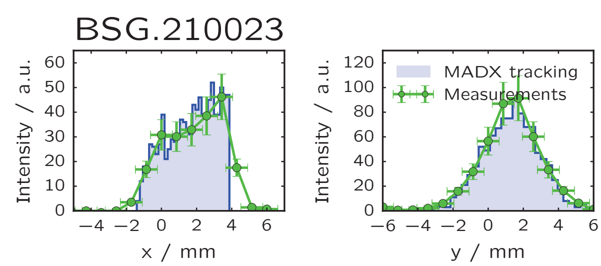

Figure 6: Horizontal (left) and vertical (right) transverse beam profile at the BSG.210023 in TT20. Measurements obtained during 2016 commissioning are shown in green. The blue shaded area are the tracking simulation results.

CONCLUSIONS AND OUTLOOK

The slow extraction is a process that needs the control and optimisation of many machine parameters. The momentum spread evolution, the spiral step, the bump amplitude and the beam transverse profiles were simulated and measured. An overall very good agreement between measurements and simulations was shown.

The developed simulation model will be used to study new configurations of the parameters, as well as to optimise the transport in TT20 (optics matching) and to try to reduce the losses at extraction.

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