PERFORMANCE OF TRANSVERSE BEAM SPLITTING AND EXTRACTION AT THE CERN PROTON SYNCHROTRON IN THE FRAMEWORK OF MULTI-TURN EXTRACTION

J. Borburgh, S. Damjanovic, S. Gilardoni, M. Giovannozzi, C. Hernalsteens*, M. Hourican, A. Huschauer†, K. Kahle, G. Le Godec, O. Michels, G. Sterbini, CERN, Geneva, Switzerland

Abstract

Considerable progress has been made in 2015 in the setting up of the Multi-Turn Extraction (MTE) in the CERN Proton Synchrotron (PS). A key ingredient in this novel extraction technique is the beam splitting in transverse phase space. This manipulation is based on adiabatic trapping in stable islands of transverse phase space and requires mastering a number of devices in the PS ring. In addition, an in-depth review of all fast extractions schemes in the PS had been required due to the development and installation of a dummy septum to shield the actual magnetic septum. In this paper, the current performance of the beam splitting and of the extraction including the shadowing effect is presented. Future lines of development will also be discussed.

INTRODUCTION

The proton beam for the fixed-target physics programme at the CERN Super Proton Synchrotron (SPS) requires a very peculiar extraction scheme from the Proton Synchrotron (PS) at 14 GeV/c. The PS extraction mode in operation until September 2015 was proposed in the early 70s [1, 2]. It is named Continuous Transfer (CT) and is based on beam slicing in the horizontal plane across the thin foil of an electrostatic septum.

Although robust, this method has some severe drawbacks. The beam-foil interaction generates high radiation levels at the location of the electrostatic septum and also in a large fraction of the PS circumference [3].

A different beam manipulation was proposed in 2002 [4]. The principle is based on the use of stable islands of low-order 1D resonances of horizontal phase space. In fact, by adiabatically crossing a resonance excited by non-linear magnetic elements such as sextupoles and octupoles, it is possible to trap particles in the separating islands. If these islands are moved towards higher phase space amplitudes the trapped beam will follow.

The transverse trapping and transport process, which efficiently replaces the slicing of CT, is performed prior to and in preparation for extraction, which is performed by a set of fast dipoles generating a closed orbit deformation lasting five machine turns. The whole process, beam splitting and extraction, has been named Multi-Turn Extraction (MTE). The time variation of the dedicated sextupoles and octupoles used to trap particles and of the RF voltage is shown in Fig. 1 (upper), while in the lower part the variation of the

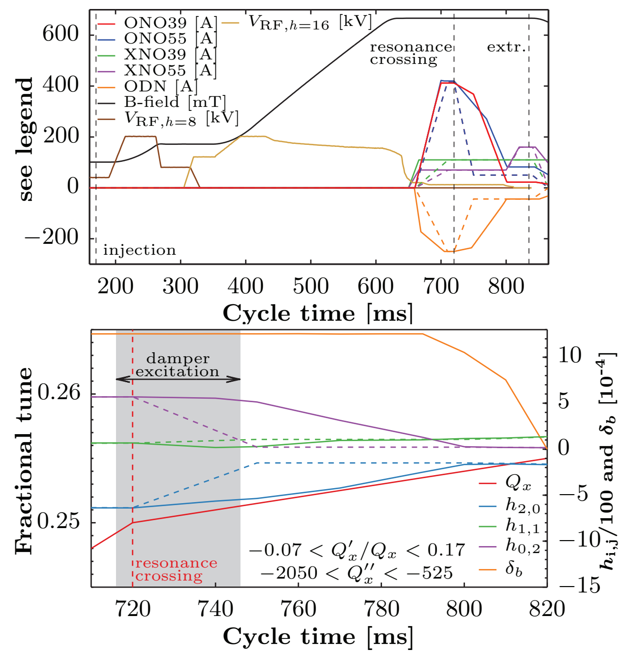

Figure 1: Upper: Time evolution of the strength of the key families of sextupoles, octupoles, and of RF voltage during the resonance crossing process. For sextupoles and octupoles the continuous curves correspond to the operational functions, and the dashed ones to simplified functions for special tests. Lower: The variation of the main beam dynamics observables is also shown. $\delta_b = 3\,\sigma_\delta$ is the bucket height and σ_δ the rms relative momentum spread.

key physical parameters is reported, assuming the notation

$$Q_x(J_x, J_y, \delta) = Q_x + 2h_{2,0}J_x + h_{1,1}J_y + Q'_x\delta + \frac{1}{2}Q''_x\delta^2 \dots$$

$$Q_y(J_x, J_y, \delta) = Q_y + h_{1,1}J_x + 2h_{0,2}J_y + Q'_y\delta + \frac{1}{2}Q''_y\delta^2 \dots$$

where δ and J_x, J_y are the relative momentum offset and the actions in the horizontal and vertical plane. The terms $h_{2,0}, h_{0,2}, h_{1,1}$ represent the detuning due to non-linear motion in the horizontal, vertical plane, and the non-linear coupling between them [5]. $Q^{(n)}_{x,y}$ are the nth order chromaticities and all coefficients are functions of the strength of quadrupoles, sextupoles, and octupoles in the PS ring [5].

Sextupole and octupole magnets are used to generate the stable islands and to control their parameters, size and position, to maximise the trapping efficiency. The coupling between horizontal and vertical motion, which could negatively affect the overall trapping efficiency, is reduced by minimising $h_{1,1}$ and the vertical emittance.

* Also at EPFL, LPAP, CH-1015 Lausanne
† Also at Vienna University of Technology, AT-1040 Vienna

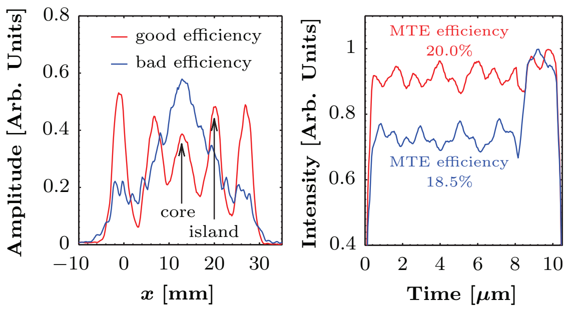

Figure 2: Left: Measured horizontal beam distribution for nominal and lower-than-nominal η_{MTE}. Right: Corresponding intensity profile measured by a beam current transformer in the transfer line between PS and SPS.

The transverse resonance is crossed by changing Q_x while keeping the vertical one constant. This variation is obtained by means of two families of quadrupoles that are distributed along the PS circumference. For 30 ms (one PS turn corresponds to 2.1 μs), mainly after the crossing of the 1/4 resonance, the beam is excited horizontally by a wide band stripline kicker, used to provide an excitation at a frequency close to the resonant tune frequency. This has shown to improve the trapping probability into the stable islands.

The RF voltage, V_{RF}, of the 10 MHz main cavity system is reduced before the resonance-crossing stage to minimise even further the coupling between the transverse and longitudinal degrees of freedom. After that, V_{RF} is set to zero to perform a complete de-bunching of the beam from the original $h = 16$ configuration. Prior to extraction a partial re-capture using a 200 MHz system is performed and the continuous beam, with an intensity modulation, is ready for transfer to the SPS where it will be re-captured using the 200 MHz main RF system.

The natural figure-of-merit of the MTE performance is

$$\text{MTE efficiency} = \eta_{\text{MTE}} = \frac{\langle I_{\text{Islands}} \rangle}{I_{\text{Total}}}, \tag{1}$$

where $\langle I_{\text{Islands}} \rangle$ and I_{Total} stand for the average intensity in the islands and the total beam intensity, respectively. The nominal efficiency is 20 %, corresponding to an equal beam population sharing between islands and core, with a minimum acceptable value of 19 % set by the SPS.

MTE COMMISSIONING

In 2010, the PS start up was performed using MTE, whereas CT was kept as a fall back option. At that time, high-intensity proton beams were delivered to the SPS for a few weeks only, as two outstanding issues were limiting the overall MTE performance [6]: both η_{MTE} and the extraction trajectories were fluctuating on a cycle-by-cycle basis. Figure 2 shows examples of fluctuations of η_{MTE}.

The second issue was the activation of the PS extraction magnetic septum, which had increased due to the debunched beam and the long rise time of the kickers, although a significant reduction of the radiation levels compared to CT operation was observed in the rest of the ring.

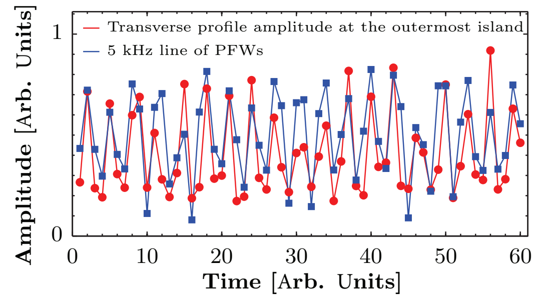

Figure 3: Time evolution of the amplitude of the beam distribution at the location of the outermost island and of the amplitude of the 5 kHz component in the PFWs current.

A dummy septum to reduce the activation of the active extraction septum was installed, with only a copper blade and no coils for the generation of magnetic field. The dummy septum intercepts protons that would otherwise interact with the blade of the active extraction septum during the extraction kickers' rise time [7]. The dummy septum solution reduces the horizontal PS ring aperture, which called for a complete review of all PS fast extraction schemes to make them compatible with the dummy septum [8–11]. The beam commissioning of the whole system and of the new fast extractions was successfully accomplished by the end of 2015.

OPERATION WITH MTE

The first positive result from a long and detailed measurement campaign, aimed at finding a physical quantity well correlated with the fluctuations of η_{MTE}, was obtained at the beginning of the 2015 run [12]. The control of the PS working point, i.e., of $Q_{x,y}$ and $Q'_{x,y}$, is achieved by means of special circuits, the pole-face-winding (PFW) coils and the figure-of-eight loop (F8L) as reported in Ref. [13] and references therein. These circuits are installed on the poles of the combined-function main dipoles and provide a transverse variation of the magnetic field, which can be used to generate quadrupolar, sextupolar, and octupolar magnetic field components. The switch-mode power converters of these circuits operate at 5 kHz (for the PFWs) and 2.5 kHz (for the F8L) and they introduce a current ripple at that frequency. The amplitude of such a component turned out to be larger-than-expected and not constant in time. The main effect of such a ripple is to change the machine parameters, thus affecting the overall efficiency of the MTE process. The very good correlation between the cycle-to-cycle variation of the transverse beam distribution after splitting and of the 5 kHz ripple amplitude is shown in Fig. 3.

As expected, damping the 5 kHz ripple component reduced the amplitude of the fluctuations of η_{MTE}, and MTE beams were transferred to the SPS for the fixed-target physics from September 21$^{\text{st}}$ until the end of the 2015 proton run on November 16$^{\text{th}}$. During this lapse of time, continuous beam optimisation was carried out, including also intensity increase, from $\approx 1.5 \times 10^{13}$ p per PS extraction at the beginning of November to $\approx 2.0 \times 10^{13}$ p, passing by an

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intermediate value of $\approx 1.8 \times 10^{13}$ p. By the end of the run, the dummy septum had been moved to its nominal position to properly shadow the extraction septum.

The evolution of beam intensity and η_{ext} is shown in Fig. 4.

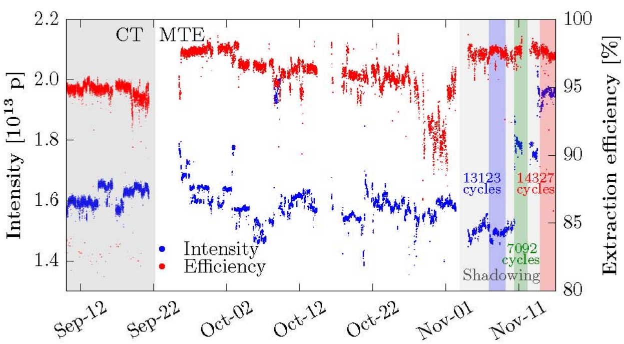

Figure 4: Evolution of PS proton intensity prior to extraction (blue) and of η_{ext} (red) for the 2015 run. The main events and the periods used for the statistical analysis are marked.

No measurable beam losses occur during the beam splitting process according to the results of the numerical simulations and theoretical predictions. Figure 5 shows the results of the measurements performed by the beam loss monitors (BLMs) located around the PS circumference in the 100 straight sections: the difference between CT and MTE is striking and fully confirms the predictions of the MTE performance.

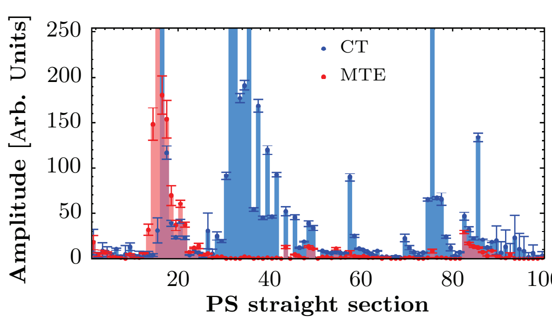

Figure 5: Distribution of extraction losses for CT and MTE around the PS ring. MTE is clearly better: losses are reduced and localised around the extraction region only. The BLM installed at the dummy septum is the only one saturated.

For MTE η_{ext} is around 97 – 98 %, whereas a typical value of η_{ext} for CT at similar beam intensity is around 95 %. Hence, MTE reduces extraction losses with respect to CT by almost a factor of 2. The distributions of η_{MTE} and η_{ext} for the three intensities used in 2015 are shown in Fig. 6, together with the cumulative distributions of η_{MTE} and the correlations for η_{MTE} and η_{ext}.

The statistical correlation for η_{MTE} and η_{ext} with beam intensity proved to be close to zero, which is an interesting result as the overall trapping performance could be potentially sensitive to space charge effects [14]. The distributions shown in Fig. 6 seem to indicate a mild dependence on intensity. They have been checked pairwise against the hypothesis

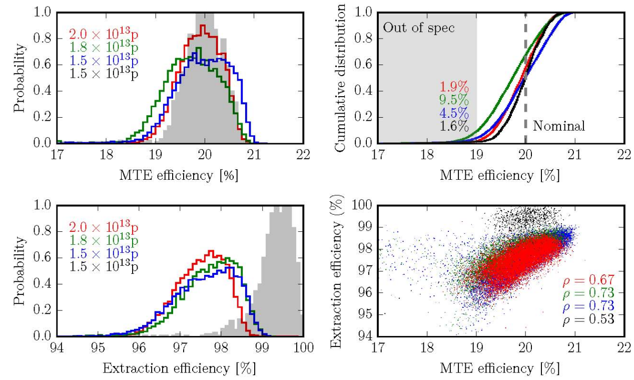

Figure 6: Upper: Distributions of η_{MTE} (left) and their cumulative distributions (right). Bottom: Distributions of η_{ext} (left) and correlation plot for η_{MTE} and η_{ext} (right).

that they are equal and the statistical analysis rejected it with a confidence level of 95 %, confirming that the visible differences are meaningful and, as these cannot be linked with intensity, are indeed the effect of the PS machine fine tuning throughout the run.

All distributions are asymmetric featuring tails towards the lower side. The correlation plot reveals a link of average strength between η_{MTE} and η_{ext}. Several mechanisms could explain this fact, and additional measurements are planned during the 2016 run to clarify this point.

In parallel to the activities for making MTE operational, studies have been carried out to further improve the MTE reproducibility. The first step has been the use of simplified functions (see Fig. 1 - dashed curves), which have been used to collect data over 10^3 cycles. The results are shown in Fig. 6 as the grey distributions. Note that during these measurements small variations of the strengths of the dedicated MTE sextupoles were made, which proved to be completely irrelevant in terms of η_{MTE} and η_{ext}. An impressive improvement in η_{ext} is clearly visible. The distribution of η_{MTE} is also more symmetric and centred around 20 %. A statistical check has been carried out to compare the meaningfulness of the differences of η_{MTE} for operational and special beams of corresponding intensity. The key point is that the symmetry could have been generated by the lack of long tails because of the limited statistic. Nonetheless, drawing several randomly-generated subsets of 10^3 cases out of the total number of cases for the operational beam, the statistical tests to check whether the two η_{MTE} distributions are the same rejected this hypothesis at 95 % confidence level.

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