Analysis of performance fluctuations for the CERN Proton Synchrotron multi-turn extraction

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Abstract. After the successful beam commissioning and tests in 2015, the Multi-Turn Extraction (MTE) has been put in operation in 2016. In this paper, the remaining issues related with fluctuation of the MTE performance are evaluated and correlation studies are presented in view of estimating the impact of planned improvements.

1. Introduction
To provide high-intensity beams for fixed-target physics at the Super Proton Synchrotron (SPS), the beam delivered by the PS has to be fully de-bunched and uniform in intensity. Therefore, the Continuous Transfer (CT) process was proposed in 1973 [1]. This extraction technique, which occurs over five turns at 14 GeV/c, allows to optimize the duty cycle as only two subsequent extractions from the PS are necessary to fill the SPS. On the downside, the CT extraction comes with the major drawback of significant beam loss occurring at multiple locations around the ring [2], leading to high dose to personnel during accelerator maintenance and repair, as well as to long cool down times.

The Multi-Turn Extraction (MTE) technique was proposed to replace the CT process in 2001 [3] in view of mitigating the shortcomings of CT. MTE is a resonant extraction mechanism, which exploits advanced concepts of non-linear beam dynamics and applies a fourth-order stable resonance to perform beam splitting in the horizontal phase space. The resulting beamlets - four islands and one core - are then extracted over five subsequent turns (see [4] for the implementation and [5] for some theory of adiabatic trapping).

Due to the complexity of the MTE scheme, its operational implementation, which came to a successful close in September 2015 (see [6, 7] for more detail), has had to overcome many challenges and, particularly, significant fluctuations in the efficiency of the transverse splitting, defined as

$$\eta_{\text{MTE}} = \frac{\langle I_{\text{Island}} \rangle}{I_{\text{Total}}},$$

where $\langle I_{\text{Island}} \rangle$ and $I_{\text{Total}}$ stand for the average intensity in each island and the total beam intensity, respectively. The nominal efficiency is 0.20, corresponding to an equal beam sharing between islands and core. This figure of merit is derived from the signal of the beam intensity in the transfer line, just downstream of the PS extraction point.

Figure 1 shows the distribution of $\eta_{\text{MTE}}$ during the 2016 physics run. The shape is quasi-Gaussian, skewed towards low values of $\eta_{\text{MTE}}$. Understanding the fine detail of this distribution
and finding means to improve it, i.e., reducing its spread, are the goal of the studies discussed in this paper.

![Figure 1. Distribution of $\eta_{\text{MTE}}$ for the 2016 physics run.](image)

**2. Analysis of fluctuations**
Figure 2 (left) shows the time-evolution of $\eta_{\text{MTE}}$ over five days. In addition to the raw data, the time series sampled over non-overlapping time intervals of 30 min is shown as well. The comparison of these signals reveals low- and high-frequency structures.

![Figure 2. Time evolution of $\eta_{\text{MTE}}$ and of its re-sampled version over non-overlapping intervals of 30 min (left) and their distributions (right).](image)

The corresponding distributions are shown in Figure 2 (right). While the distribution of the raw data is quasi-Gaussian, this is by far not the case for the low-frequency contribution. These features suggest a different physical source and, therefore, different mitigation strategies to the fluctuations of $\eta_{\text{MTE}}$. In fact, the low-frequency variations can be cured by a slow feedback
or by a human intervention, while the high-frequency components cannot. Therefore, most of the efforts have been devoted to finding the sources of the high-frequency variation in view of correcting them at the source.

An example of the time-variations that can be corrected by a human intervention is given in Figure 3 (upper), where a slow drift of the PS transverse tunes is shown together with the change in $\eta_{\text{MTE}}$ (lower).

![Figure 3](image)

**Figure 3.** Upper: Time evolution of $\Delta Q_H$ and $\Delta Q_V$. Lower: Time evolution of $\eta_{\text{MTE}}$. The continuous lines represent the re-sampled version over non-overlapping intervals of 5 min.

Even though the origin of the tune drift is not known, the time scale is such that the variation can be compensated by means of the PS ring tuning quadrupoles. Another example is given by the impact of the change of the PS magnetic configuration on $\eta_{\text{MTE}}$, shown in Figure 4. A step variation is clearly visible, which is likely to be generated by a change in the hysteresis of the combined-function main magnets. Also in this case the change in $\eta_{\text{MTE}}$ can be easily compensated by acting on the horizontal tune.

### 3. Correlation analysis

The main source of the high-frequency fluctuations was identified as the 5 kHz ripple component of the converters powering the additional coils installed in the main magnets [6]. The clocks of these six power converters are not synchronised, thus generating a time-dependent ripple component. The excellent correlation between the amplitude variation of this ripple component and $\eta_{\text{MTE}}$ is shown in Figure 5 (upper). The measurement device installed in a reference magnet provides the value of $dB/dt$. 


Figure 4. Time evolution of $\eta_{\text{MTE}}$ during a change of PS magnetic configuration (indicated by the change of colour of the background).

Figure 5. Upper: Time evolution of $\eta_{\text{MTE}}$ and of the amplitude of the 5 kHz current ripple component on the power supplies. Lower: Time evolution of the variation of extraction conditions of first island ($\Delta H_1$) and of core ($\Delta H_5$).

Hence, the observed $\pi/2$ phase difference between $\eta_{\text{MTE}}$ and $dB/dt$ turns into a $\pi$ phase difference with the $B$-field, which then is in counter phase with $\eta_{\text{MTE}}$. All this is a sign of the good correlation between the two quantities, not to mention that the two quantities feature a very similar time variation. It is also interesting to inspect the behaviour of the horizontal...
extraction position as a function of time. To analyse the trajectory stability of the extracted beam, a pick-up in the transfer line just downstream of the PS extraction septum is used to determine the position of each extracted turn. The average position over several extractions is subtracted from the measured value and the result is indicated by $\Delta H_i, 1 \leq i \leq 5$. The analysis showed that $\Delta H_i, 1 \leq i \leq 4$ are all well correlated between them, as expected, so that it is sufficient to consider in the analysis only $\Delta H_1$ and $\Delta H_5$, i.e., the horizontal variation of the extraction condition of the first island and of the core, respectively. Their time evolution is shown in Figure 5 (lower): while $\Delta H_5$ is almost constant, with a variation close to the pick-up resolution, $\Delta H_1$ changes considerably. Furthermore, the frequency content appears different with respect to the 5 kHz ripple component. This behaviour, however, does not imply that the fluctuations of $\Delta H_1$ are not related with the ripple. In fact, the ripple affects $\eta_{MTE}$ during the resonance crossing stage extending over several tens of ms, so that its phase is irrelevant. On the other hand, the extraction conditions are indeed sensitive not only to the amplitude, but also to the phase of the 5 kHz component with respect to the extraction time.

This analysis can be further pursued by checking the autocorrelation of $\eta_{MTE}$ and $\Delta H_1$, as shown in Figure 6. The former quantity features a rather regular pattern, showing that a strong correlation (positive or negative) occurs for time intervals slightly over one minute, while $\Delta H_1$ features a slightly weaker autocorrelation, much richer in frequency content. The striking point is the close resemblance of the autocorrelation of $\eta_{MTE}$ and $\Delta H_1$ with that of the amplitude and phase of the 5 kHz component, respectively. All this is clearly visible in Figure 6, thus confirming that the ripple is the source of both $\eta_{MTE}$ fluctuations and $\Delta H_1$ variations.

![Figure 6. Autocorrelation of $\eta_{MTE}$ (blue) and $\Delta H_1$ (red).](image)

From an operational point of view, given that two extractions from the PS are needed to fill the SPS ring, the performance of consecutive extractions should be very similar. This turns out to be the case as can be seen in Figure 7, where the correlation between the two extractions for $\eta_{MTE}$ and $\Delta H_1$ is clearly visible.

The last aspect analysed is the correlation between fluctuations and extraction losses. To this aim, the signal from a beam loss monitors (BLM) installed close to the extraction septum (SS16) has been used (see also [6, 8]). The BLM detects two loss spikes generated by the continuous beam during the rise time of the extraction kickers, when the islands and then the core are
Figure 7. Correlation plot of two consecutive extractions for $\eta_{\text{MTE}}$ (left) and for $\Delta H_1$ (right). The correlation coefficients for $\eta_{\text{MTE}}$ and $\Delta H_1$ are 0.84 and 0.74, respectively.

extracted. These two spikes are individually integrated and correlated with $\eta_{\text{MTE}}$ in Figure 8. The best correlation between $\eta_{\text{MTE}}$ and beam losses is observed for the core.

Figure 8. Correlation plot of losses for islands (left) and core (right) and $\eta_{\text{MTE}}$. The correlation coefficients for islands and core losses are $-0.19$ and $-0.75$, respectively.

The observation that the core-induced beam losses are closely connected with the fluctuations of $\eta_{\text{MTE}}$ is confirmed by the result that the core width is well correlated with $\eta_{\text{MTE}}$ as shown in Figure 9. The core width can be estimated by means of a diamond BLM also installed in SS16. In fact, the time-response of a diamond BLM is fast enough to ensure that the FWHM of the loss spike is proportional to the beam width.

The results shown in Figure 9 indicate that a smaller core size implies a larger $\eta_{\text{MTE}}$ and hence lower losses at extraction.
Figure 9. Correlation between core size and $\eta_{\text{MTE}}$. The correlation coefficient is $-0.54$.

4. Conclusions and outlook
The efforts devoted to the understanding of the fluctuations of $\eta_{\text{MTE}}$ are paying off. The mitigation measures put in place in 2015 to reduce the amplitude of the 5 kHz ripple of the power converters of the auxiliary coils in the PS main magnets made MTE a suitable operational replacement of CT. The measurements and analysis presented in this paper confirm that $\eta_{\text{MTE}}$ correlates well with the power converter ripple. For this reason the controls of the power converters have been upgraded during the 2016-17 winter shut down so to allow synchronising the clocks and to double the ripple frequency, thus shifting it outside of the beam spectrum [8]. New current transformers have been installed to provide a direct current measurement for the auxiliary circuits and should provide additional information to assess which field component affects $\eta_{\text{MTE}}$ and $\Delta H_1$. The new observations presented here indicate that curing the ripple should have a beneficial impact on the reproducibility of the extraction trajectories and should lower extraction losses, whose fluctuations are linked with the beam core size. Finally, after the successful reduction of the high-frequency $\eta_{\text{MTE}}$ fluctuations, only the low-frequency components will remain.

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