

# RESULTS FROM THE 2009 BEAM COMMISSIONING OF THE CERN MULTI-TURN EXTRACTION

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## Abstract

Following the analysis of the results obtained during the first year of beam commissioning of the CERN multi-turn extraction, a number of changes have been introduced in the beam manipulations performed in the CERN Proton Synchrotron. This includes a different control of the linear chromaticity, the setting of the non-linear magnets used to split the beam, and the longitudinal structure in the PS. The results obtained during the 2009 run are presented and discussed in detail, including the beam performance in both the PS and the SPS.

## INTRODUCTION

Since some time, a new system to deliver beam to the SPS is under study at CERN [1]. The idea is to extract the beam over five turns by using a splitting in the transverse plane, the so-called multi-turn extraction (MTE) instead of slicing it by means of an electrostatic septum, the so-called continuous transfer (CT) [2]. After a study phase [3] the hardware installation was completed in 2008 and the beam commissioning started in the same year [4]. At the end of 2008 it was possible to extract a moderate intensity beam of about  $1.3 \times 10^{13}$  p per PS extraction towards the SPS with a bunched structure on  $h=16$ . During the year 2009 three main objectives needed to be tackled, namely: i) to increase the beam intensity up to about  $2.3 \times 10^{13}$  p per PS extraction; ii) to improve the spill profile, i.e., to improve the intensity sharing between the first four extracted turns and the last one; iii) to set-up the transverse splitting so that the beam delivered to the SPS is de-bunched. These three items will be described in details in this paper.

It is worth mentioning that due to extremely short winter shutdown at the end of the 2009 physics run, imposed by the schedule of the LHC beam commissioning, it was possible to resume the MTE beam commissioning already by mid-February 2010. Therefore, this paper will report also about the status until the beginning of the 2010 physics run in May 2010, thus covering a longer time span than quoted in the title.

## TRANSVERSE SPLITTING STUDIES

A review of the transverse splitting process was performed. The variation of the strength of the non-linear elements generating the stable islands was optimised in order to maximise the fraction of beam trapped inside.

Detailed measurements were performed by scanning of the various parameters and measuring the transverse beam profiles after splitting in order to evaluate the key figure-of-merit, i.e., the trapping fraction. The most effective parameter turned out to be the strength of the two octupoles located in straight section 39 and 55 of the PS machine. It is worth stressing that unlike previous year, special care was taken to minimise the non-linear coupling generated by the octupoles.

In fact, even if they are located in a region where the horizontal beta function reaches its maximum value and the vertical its minimum, with a ratio of about 2, the non-linear coupling is not completely negligible. This means that the horizontal detuning with amplitude  $\delta v_x$  depends on the vertical amplitude  $\rho_y$  of the particle according to

$$\begin{aligned} \delta Q_x &= h_{2,0} \rho_x + h_{1,1} \rho_y \\ \delta Q_y &= h_{1,1} \rho_x + h_{0,2} \rho_y \end{aligned} \quad (1)$$

thus affecting the resonance crossing process and hence the probability of trapping in the stable islands. Therefore, the circuit of octupoles located at large vertical beta-function, normally used to combat instabilities, were powered to reduce the coupling. In Fig. 1 the result of scans over the strength of the octupoles (generating the stable islands) and of the circuit correcting the non-linear coupling is shown. In Fig. 2 the functions after full optimisation are reported.

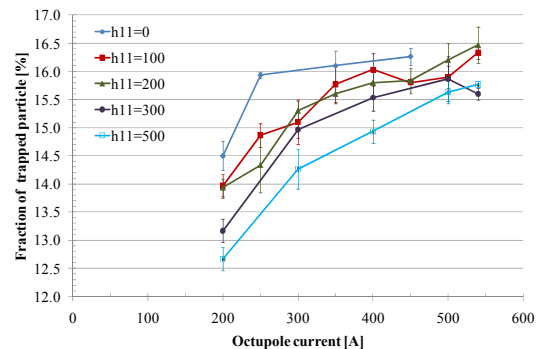


Figure 1: Evolution of the fraction of trapped particles vs. strength of octupoles for different values of the non-linear coupling coefficient  $h_{11}$ .

Even after this optimisation the sharing among the five beamlets was not equal. This was considered to be an effect of the strong  $Q''$  term, which is driving particles outside the resonance in case of too large a momentum offset, or due to the untrapped particle in the beam core.

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Therefore, it was decided to perform tests by exciting the beam using a transverse damper during the resonance crossing stage: this should have the effect of enhancing the trapping probability. The test was performed by exciting the beam at a frequency equal to  $f_{\text{rev}}(16+0.25)$  with a fm-modulated signal around such a carrier frequency. The very encouraging results are shown in Fig. 3: since these tests the transverse damper is used to excite the beam and provide a better sharing for the spill.

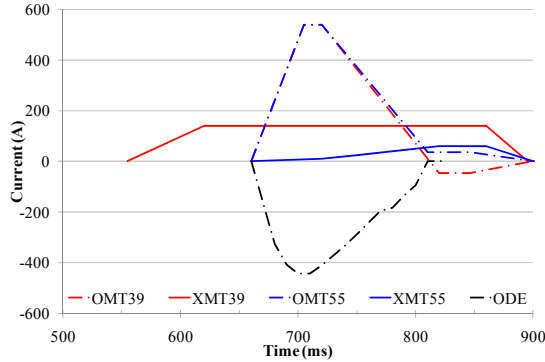


Figure 2: Evolution of the currents of the non-linear magnets (sextupoles and octupoles) in straight sections 39 and 55 as a function of time along the magnetic flat top, which starts at about 650 ms. Extraction occurs at 835 ms.

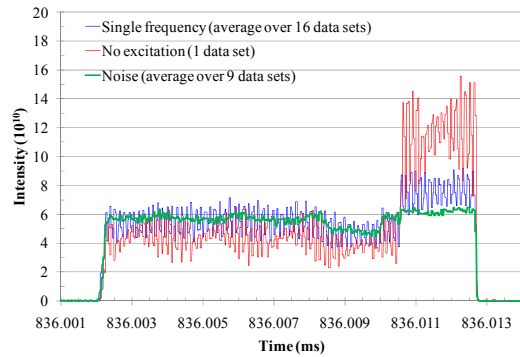


Figure 3: Extracted spill with different types of transverse excitation.

## LONGITUDINAL BEAM DYNAMICS

The preferred longitudinal structure for injection into the SPS is a debunched beam. In principle, this structure could be obtained by reducing the RF voltage already before sweeping through the transverse resonance. This would have the advantage of freezing the longitudinal motion during transverse splitting and minimising the momentum spread. The issue encountered is a longitudinal microwave instability that blows up the momentum distribution. In Fig. 4 longitudinal beam spectra for two different intensities are shown. The duration when the beam remains debunched depends on intensity, but some coherent signal, sign of rebunching due to the instability, is always observed. Furthermore, for the higher intensity an increase of the momentum

spread is clearly seen. This is certainly detrimental to the transverse splitting as the  $Q''$  drives particles with increased momentum spread far from the resonance, thus reducing the fraction of trapped particles.

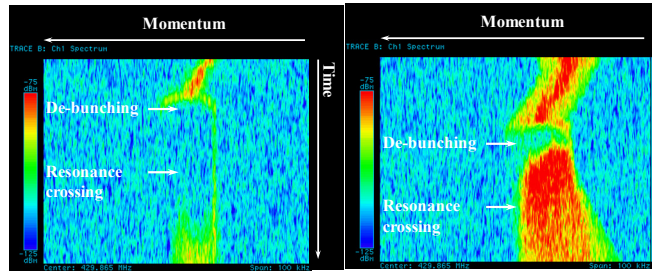


Figure 4: Longitudinal beam spectra for debunched ( $h=903$ , 430 MHz) beam at 14 GeV/c flat top for  $0.4 \times 10^{13}$  p (left) and  $1.7 \times 10^{13}$  p (right).

Therefore, rather than keeping the beam debunched for a long period, it is kept with a relatively low RF voltage (about 8 kV generated by one single cavity, the others being in short circuit with gap closed) and then debunched after the transverse splitting is completed, just prior to extraction. The RF-voltage as a function of time along the magnetic cycle, as well as the variation of the harmonic number is sketched in Fig. 5.

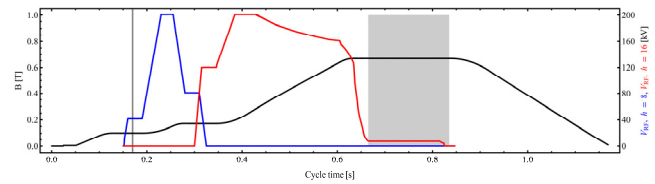


Figure 5: Magnetic field (black) and RF voltage ( $h=8$ , blue;  $h=16$ , red) for the whole magnetic cycle. The shaded area corresponds to the transverse splitting gymnastics.

This choice improves the situation in the sense of providing a rather controlled value of the momentum spread, even if it does not prevent the beam to become unstable. Indeed, a longitudinal coupled-bunch instability of quadrupolar mode [5] is observed (Fig. 6).

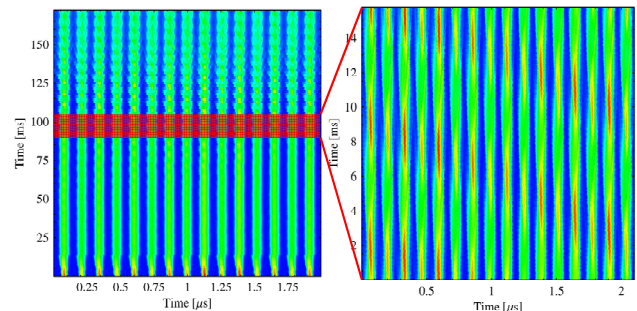


Figure 6: Evolution of the longitudinal bunch profiles with low RF-voltage on the flat top (the origin of the time scale corresponds to 700 ms of Fig. 5.).

Recently [6], ways of stabilising this instability by means of a one-turn delay feedback have been studied successfully and their impact on MTE will be evaluated.

## 2010 PERFORMANCE

Following the outcome of the commissioning studies, the decision has been taken to start up the 2010 physics run based on the MTE, only, without setting up the CT beam. The current performance can be summarised as follows:

- Beam for fixed target physics at the SPS: the MTE beam is routinely delivering an intensity of about  $1.5 \times 10^{13}$  p per PS extraction. The extraction efficiency is about 98 % and the distribution of extraction efficiency is shown in Fig. 7.
- Beam for CNGS physics: the beam is routinely delivered at an intensity of about  $2.1 \times 10^{13}$  p per PS extraction. The extraction efficiency is about 97 % and the distribution of extraction efficiency is shown in Fig. 7.

Average spills measured during the beginning of the physics run at the end of April 2010 are shown in Fig. 8. The vertical scale is in arbitrary units and only the ratio between the first four turns and the fifth one is relevant.

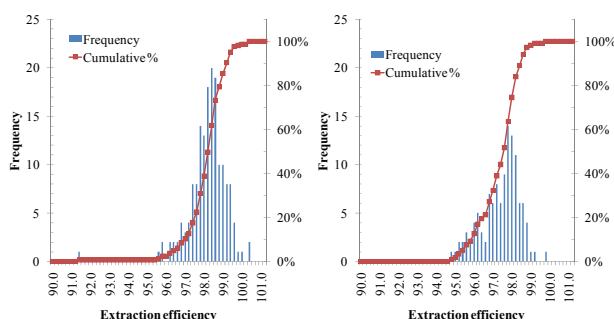


Figure 7: Distribution of extraction efficiency for the beam for fixed target physics (left) and CNGS (right).

The two pictures indicate that the spill shape is varying and is less stable for the higher intensity beam.

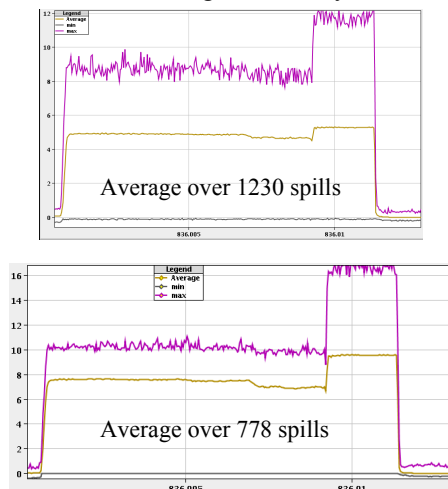


Figure 8: Average spill shape (yellow) for the fixed target physics beam (upper) and the CNGS one (lower). The purple curve represents the worst spill.

Indeed, the losses at PS extraction reveal a regular pattern with periodic variation over a short time scale as

seen in Fig. 9: this feature is the focus of the current activities for MTE commissioning and operation.

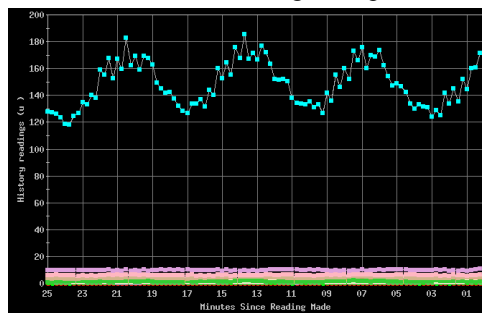


Figure 9: Time variation of the losses measured on the beam loss monitor installed on top of the extraction septum. The vertical scale is in  $\mu\text{Sv/h}$ .

## CONCLUSIONS AND OUTLOOK

A substantial improvement of the overall performance with respect to what was obtained during the 2008 commissioning run was achieved during the 2009/2010 runs. In particular, the intensity at extraction from PS was ramped up to the nominal one required for CNGS operation, corresponding to about  $2.3 \times 10^{13}$  p. Extraction efficiencies as high as 98 % were obtained. Furthermore, injection losses in the SPS and overall transmission, i.e., from injection to extraction towards the targets, were comparable to the routine operation with the classical CT transfer.

Two main points are under consideration and will be the main focus of the 2010 activities, namely:

- Improvement of the spill reproducibility at PS extraction and understanding of the periodic variations observed so far.
- Reduction of the activation of extraction magnetic septum due to the unavoidable losses linked to the longitudinal beam structure required by the SPS.

## ACKNOWLEDGEMENTS

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