FIRST OBSERVATIONS OF INTENSITY-DEPENDENT EFFECTS FOR TRANSVERSALLY SPLIT BEAMS

Simone Gilardoni, Massimo Giovannozzi, CERN, Geneva, Switzerland

Abstract

During the commissioning of the CERN PS Multi-Turn Extraction (MTE) tests with different beam intensities were performed. The initial beam current before transverse splitting was varied and the properties of the five beamlets obtained by crossing the fourth-order horizontal resonance were studied. A clear dependence of the beamlets' parameters on the total intensity was found, which is the first direct observation of intensity-dependent effects for such a peculiar beam type. The experimental results are presented and discussed in this paper.

INTRODUCTION

The multi-turn extraction (MTE) [1,2] has been proposed as a new beam manipulation in the transverse plane. The idea is to cross a resonance featuring stable islands. The beam will be eventually trapped in the stable islands as they sweep through the phase space area occupied by the charged particles. As a result of this gymnastics, the beam will be split in the transverse plane: in case the resonance is stable, two structures will be generated: one representing the beam trapped in the islands, with an effective length corresponding to the machine length times the resonance order; the second one, made of the beam left over in the centre of the phase space, with a length corresponding to a single machine circumference. In case of unstable resonances, a single structure with a length corresponding to a multiple, equal to the resonance order, of the machine circumference is generated.

Another important difference between the use of the stable vs. unstable resonance is that the latter will automatically generate equally populate structures, while the stable resonances do not guarantee that the beam intensity is equally shared among the two disconnected structures. Once the resonance is crossed and the beam split, it is then possible to extract the charged particles over many turns corresponding to the order of the resonance used for the splitting and its stability type.

It is worth emphasising that such an extraction method is aimed at providing the most uniform filling of a receiving machine of different circumference from the one of the extracting machine. At CERN, this is the case for the Protron Synchrotron (PS) transfer to the Super Proton Synchrotron (SPS) for the fixed target physics. The current extraction method, the so-called Continuous Transfer (CT) [3] is being gradually replaced by MTE in its PS implementation [4] (see Refs. [5, 6] for the original accounts on the experimental results, and Ref. [7] for an account of the commissioning efforts).

This manipulation can be easily generalised to other situations, as it could be used to perform multi-turn injection (MTI) are described in [8] with some advantages, in terms of final value of the beam emittance, with respect to the classical multi-turn injection. In this framework a first glance at space charge effects was made and reported in [9]. Clearly, injection is certainly more prone to space charge effects than extraction. On the other hand a first estimate of possible space charge effects for MTE was outlined already in [1]. For the CERN-specific application, the typical intensities and the extraction energy of 14 GeV/c made the tune shift due to space charge of the order few 10^{-3}. Hence, it is not completely negligible, but very likely tolerable for the proposed manipulation. During the commissioning stage, although no specific measurement was planned to study intensity-dependent effects for MTE, nevertheless it was possible to probe the very existence of space charge effects. These measurements represent the core of this paper.

EXPERIMENTAL CONFIGURATION

General PS machine setting

In Fig. 1 the evolution of the main machine parameters as a function of time is shown during the whole magnetic cycle of 1.2 s.

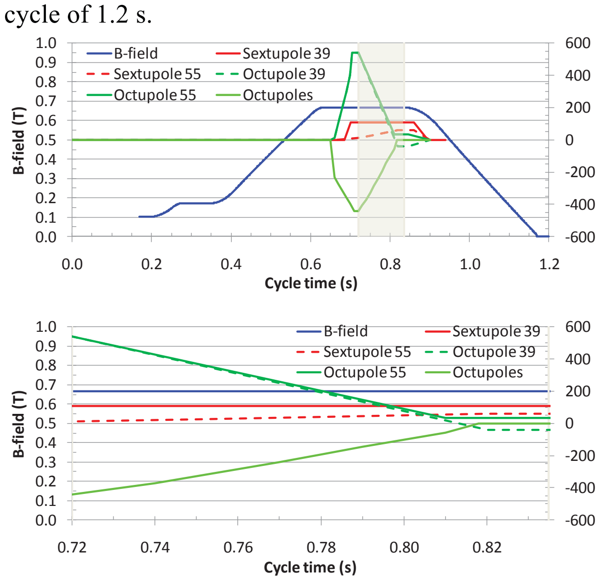

Figure 1: Overview of the MTE gymnastics (upper). The magnetic cycles is shown together with the evolution of the current in the non-linear elements used for generating the stable islands and correcting the non-linear coupling. The shaded area represents the region where the transverse splitting takes place: the zoom of this region is shown in the lower plot. The numbers after the elements indicate the straight section in which they are installed.

The beam is injected at 1.4 GeV (kinetic energy) and extracted at 14 GeV/c. At flat-top, prior to extraction, sextupoles and octupoles are powered to generate stable islands, while special quadrupoles are used to cross the fourth-order resonance. The non-linear magnets introduce an unavoidable non-linear coupling between the two transverse planes as indicated in the following

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

where $h_{2,0}$, $h_{0,2}$ represent the detuning with amplitude in the horizontal and vertical plane, respectively, and $h_{1,1}$ the coupling term between the two planes.

The global picture concerning the time-evolution of the key beam dynamical quantities during the transverse splitting process is shown in Fig. 2.

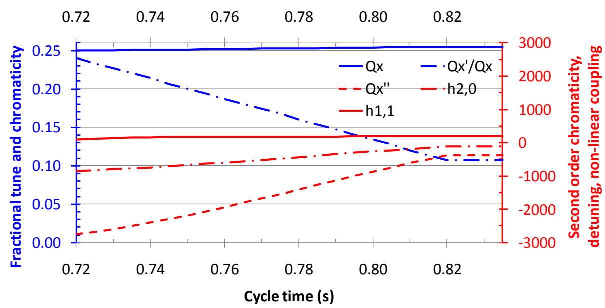

Figure 2: Overview of the time-evolution of the main parameters $h_{2,0}, h_{0,2}, h_{1,1}$ together with the horizontal tune and the linear and second order chromaticity during the splitting process.

The linear chromaticity is decreased during the resonance-crossing stage in order to reduce as much as possible the transverse/longitudinal coupling and the non-linear coupling is kept constant and small thanks to a special circuit of octupoles. The various circuits are then kept to a constant value starting from 0.82 s from the beginning of the magnetic cycle: during this state, when no beam manipulation is performed, the transverse beam profile in the horizontal plane is measured to extract the dependence of the beamlets' parameters from the intensity of the beam.

As far as the longitudinal structure is concerned [7], a maximum of height bunches are injected from the PS-Booster and then split into sixteen at 3.5 GeV/*c*. Finally, at top energy a voltage reduction is applied in order to increase the bunch length and hence reduce the momentum spread to further decouple the longitudinal motion form the transverse one during the resonance crossing. Then, just prior to extraction, the beam is completely de-bunched [7].

PS-Booster beam

It is worth reminding that the intensity of the injected beam into the PS is controlled by the PS-Booster. The number of turns injected from the Linac2 enables to vary the beam intensity. However, the resulting transverse emittance is not independent from the intensity. In the experiment described in this paper the PS intensity was controlled by means of the number of injected turns into the PS-Booster. Nevertheless, in few cases, the number of injected turns was kept constant, but the number of bunches injected in the PS was varied, thus leaving some empty buckets. It is clear that reducing the number of bunches allows changing the total beam intensity while keeping the same transverse emittance.

The situation is clearly seen in Fig. 3, where the horizontal beam size measured with a wire scanner at PS top energy is plotted as a function of beam intensity.

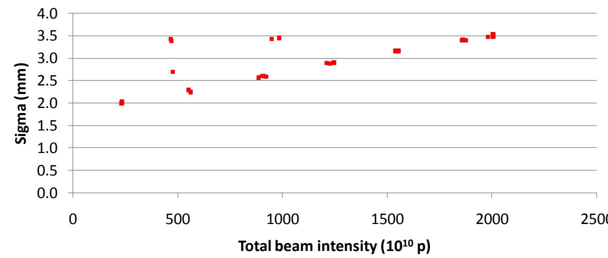

Figure 3: Horizontal beam size before resonance crossing as a function of the total beam intensity. A linear dependence is clearly visible, due to the multi-turn injection process in the PS-Booster. The outliers represent the cases in which the number of bunches has been reduced.

The linear relationship between intensity and horizontal beam size is clearly visible. The few outliers represent the cases for which the intensity has been varied by reducing the number of injected bunches in the PS, which allows keeping the transverse beam size constant. In particular, these special cases have been obtained starting from the highest intensity beams and reducing by two or four the total number of injected bunches.

MEASUREMENT RESULTS

These tests were performed by injecting variable intensity proton beams in the PS. Then, just prior to resonance crossing a horizontal beam profile was measured using the wire scanner in straight section 64 to monitor the beam size and have a cross-check of the intensity before the splitting process. Finally, at around 0.82 s from the beginning of the magnetic cycle a second horizontal beam profile was measured to extract the relevant information from the beamlets after splitting. Each case, corresponding to a given intensity, was repeated three times to have a minimum statistics. In Fig. 4 the superposition of the various beam profiles after splitting for the various beam intensities is shown. The five beamlets, representing the core left after resonance crossing and the particles trapped in the stable islands, are clearly visible as five Gaussian profiles. It is also clearly seen that, while the core is unaffected, in terms on mean position and sigma, by the different total beam intensity, the beamlets' are indeed showing some dependence, as the position is changing with the total beam intensity. A more quantitative analysis is performed by fitting five Gaussian distribution functions studying the behaviour of average and sigma as a function of intensity. In Fig. 5 (upper) the position of the four Gaussians vs. intensity is shown. A clear, linear trend is visible. The slopes of these lines are different due to the projection effects of the islands' position from phase space to real space. The error bars associated to the estimate of the average position of the beamlets is given by the least square fit procedure.

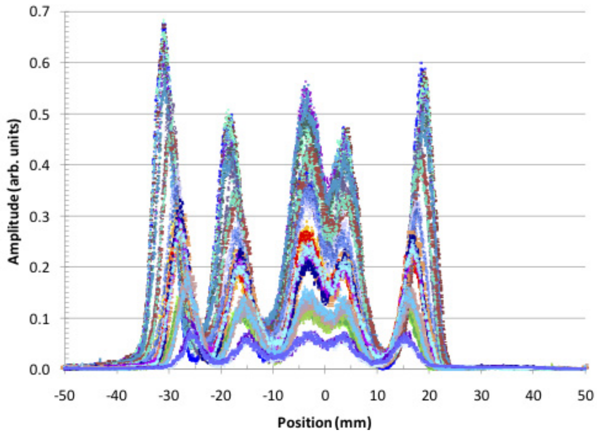

Figure 4: Superposition of the horizontal beam profiles measured after splitting for various beam intensities. The displacement of the four outermost beamlets is visible.

The smaller emittance obtained for low intensity beams generates a lower fraction of trapped particles and hence a lower quality for the Gaussian fit, which explains the increased size of the errors bars towards lower intensities. The sigmas of the beamlets are intensity independent.

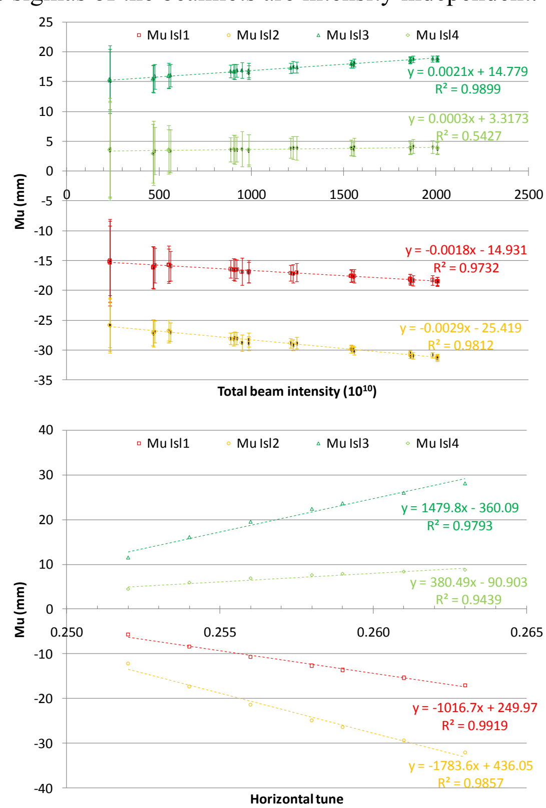

Figure 5: Beamlets position vs. intensity (upper) from the fit of the profiles showed in Fig. 4. Fixed point position vs. horizontal tune (lower) from the numerical PS model.

This led us to conjecture that the main effect of space charge interaction for split beams is an incoherent tune shift. In fact, the beamlets position is, among other, affected by the value of the linear tune: a space charge-induced tune shift would, therefore, change the final beamlets position. The numerical model of the PS machine [10] was used to estimate the position of the fixed points of the fourth order resonance as a function of the linear tune (Fig. 5 – lower). Using the values from the weighted fits of the curves in Fig. 5 (upper), the fixed point dependence on tune, tune shift as a function of intensity can be computed. The weighted average of the results for the four islands gives

$$\begin{gathered} Q_x = Q_{x,0} + m\,I \\ m = (134.9 \pm 8.0)\times 10^{-8}, \quad Q_{x,0} = 0.257 \pm 0.033 \end{gathered} \tag{2}$$

where I stands for the total beam intensity (in units of 10^{10}) and the errors are derived from the fit errors.

CONCLUSIONS AND OUTLOOK

Intensity-dependent effects for transversely split beams have been observed during the commissioning of the CERN MTE. Particular emphasis is given to the interpretation of the beamlets' position vs. intensity as an incoherent tune shift effect, which was estimated using the theoretical model of the PS machine. It is clear that numerical simulations should be performed to further the understanding of the observations. Furthermore, it will be important to disentangle the contribution to the tune shift from the direct space charge and the image currents on the vacuum pipe. In both cases, no estimate is currently available for these special beams and dedicated theoretical investigations will be needed.

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