FINAL RESULTS FROM THE NOVEL MULTI-TURN EXTRACTION STUDIES AT CERN PROTON SYNCHROTRON

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Abstract

Recently a novel approach to perform multi-turn extraction was proposed based on beam splitting in the transverse phase space by means of trapping inside stable islands. An experimental campaign was launched since the year 2002 to assess the feasibility of such an extraction scheme at the CERN Proton Synchrotron. During the year 2004 run, a high-intensity single-bunch beam was successfully split and the generated beamlets separated without any measurable losses. The latest experimental results are presented and discussed in details in this paper. These achievements represent a substantial step forward with respect to what achieved in previous years, as only a low-intensity bunch could be split without losses. Furthermore, this opens the possibility of using such a technique for routine operation with the high-intensity proton beams required for the planned CERN Neutrino to Gran Sasso Project.

INTRODUCTION

Since the year 2001, intense efforts were dedicated to the study of a novel technique to perform multi-turn extraction from a circular particle accelerator. Such a technique relies on the use of nonlinear magnetic fields, sextupolar and octupolar, to generate stable islands in the horizontal transverse phase space. By means of an appropriate tune variation, a specific resonance is crossed, the fourth-order in the case under study, and the beam is split by trapping inside the stable islands that move from the origin of the phase space towards higher amplitudes [1-4].

An example of the change of the phase space topology during the resonance-crossing is shown in Fig. 1, which is obtained by using a numerical model of a FODO cell with a sextupole and an octupole located at the same longitudinal position, both represented in the single-kick approximation [5] (for the application under study, only the horizontal plane is relevant, hence, the dynamics of such a system is generated by a 2D polynomial one-turn transfer map of order three [4, 5]).

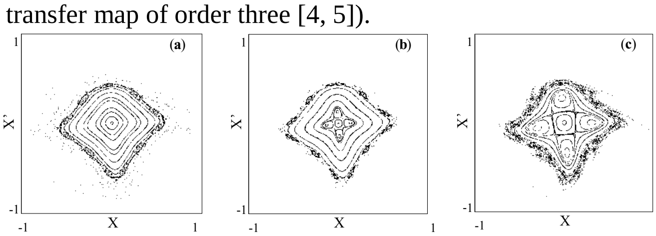

Figure 1: Topology of the normalised phase space during resonance crossing.

The evolution of the beam distribution during the resonance crossing is shown in Fig. 2.

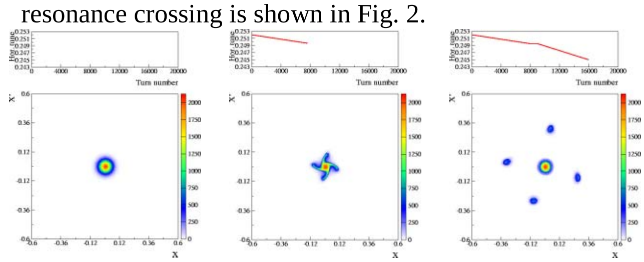

Figure 2: Evolution of the beam distribution during resonance crossing: the initial state is represented by a bi-Gaussian beam (left), at resonance-crossing some particles are trapped inside the moving islands (centre), at the end of the process, the particles trapped in the islands are moved towards higher amplitudes (right).

When the tune is changed the islands move through the phase space region where the charged particles sit and some are trapped inside the islands. At some stage a complete separation between the beamlets and the central core occurs and the distance between the beamlets can be increased at will by simply acting on the tune. It is worthwhile stressing that the beam after trapping has a peculiar structure, being made by two disconnected parts, namely the beamlets, which are indeed one single structure closing-up after four machine turns (see Fig. 3), and the central core.

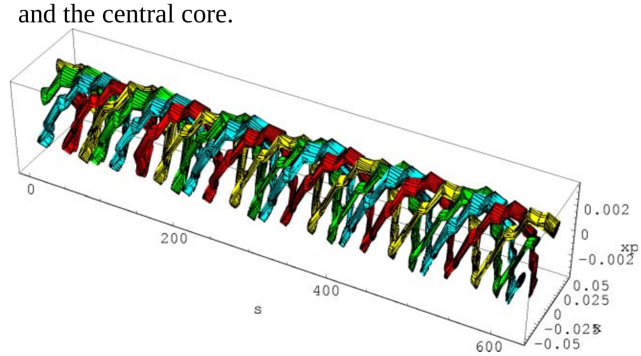

Figure 3: 3D view of the beamlets along the circumference of the PS ring. Although this is a single structure four-turn long, four colours have been used to ease the visualisation. The fifth beamlet, corresponding to the central core, is not shown here.

The idea behind this process is that such a beam splitting in the transverse phase space can be used to perform multi-turn extraction. In fact, once the various beamlets are separated, the whole structure can be pushed towards an extraction septum by means of a closed slow bump. Then, kicker magnets generate a fast closed bump and one island jumps beyond the septum blade so that the

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beamlets are extracted out of the machine in four turns. The fifth beamlet, i.e. the central core, is extracted using a classical single-turn extraction.

The choice of the resonance to be crossed is completely arbitrary: the use of a fourth-order resonance is dictated by the CERN-specific application. The extraction mode from the Proton Synchrotron (PS) to the Super Proton Synchrotron (SPS) foreseen to deliver the high-intensity proton beam for the planned CERN Neutrino to Gran Sasso (CNGS) experiments [6] is the so-called Continuous Transfer (CT) [7]. The beam is sliced onto an electrostatic septum and it is transferred to the SPS in five turns. The main drawback of such an extraction technique is the high losses in the septum, generating serious problems for the hands-on maintenance and lifetime of the device. Furthermore, the extracted slices feature different shapes in phase space, thus inducing betatron mismatch at injection in the receiving machine and, eventually, emittance blow-up [8, 9]. These points represent serious obstacles for the planned intensity upgrade for the CNGS beam [10].

The goal of the study presented here consists in achieving beam splitting with virtually no losses of a beam made by eight bunches, accelerated to 14 GeV/*c*, of about 5-6×10^{12} protons/bunch.

EXPERIMENTAL RESULTS

Overall Measurement Strategy

In parallel with the computational and theoretical analysis of the problem, an intense experimental campaign was launched since the end of year 2001 [11-13] on the CERN PS. This entailed the development of new measurement systems, such as the turn-by-turn orbit measurement system [14, 15], as well as the installation of sextupoles and octupoles to generate the stable islands.

The magnetic elements and the beam instrumentation used in the experimental campaign are shown in Fig. 4. The tune is changed by means of two families of focusing and defocusing quadrupoles, normally used to tune the machine. Sextupoles and octupoles are used to generate the stable islands; the extraction kicker is used to displace the beam and induce betatron oscillations for phase space measurements; a wire scanner [16] is used to measure the horizontal beam profile; two pickups are used to record the betatron oscillations.

The overall strategy for the experimental campaign was based on three stages:

<u>Measurement of the phase space topology</u>. This is performed by displacing a low-intensity, single-bunch, pencil beam, by means of the extraction kicker. The betatron oscillations measured by two pickups are then recorded on a turn-by-turn basis and analysed to detect the presence of stable islands. The position signal features a decoherence, due to beam filamentation induced by nonlinear effects and chromaticity. Whenever the beam is displaced inside one island, the natural decoherence is almost completely suppressed. Also, the so-called secondary frequency [5] can be measured as well as its amplitude dependence to evaluate a sort of detuning curve [17].

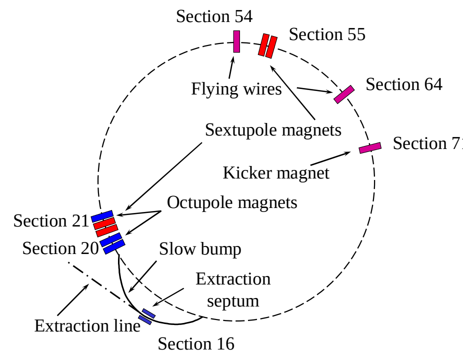

Figure 4: Schematic layout of the PS ring with the elements used for the experimental study of the novel multi-turn extraction.

<u>Trapping measurement with a low-intensity beam</u>. The key measurement, i.e. the verification of the splitting due to resonance-crossing is usually performed first with a low-intensity, single-bunch beam. This has the advantage of suppressing any possible effect due to Coulomb interaction between the protons in the bunch.

Furthermore, a special care is devoted at the level of the PS-Booster ring, the PS injector, when generating this special beam. In fact, the larger the horizontal emittance of the initial beam, the more efficient the trapping is. Therefore, the beam is artificially blown-up in the horizontal plane, while keeping the vertical emittance as small as possible. Ideally, the horizontal emittance should have as much as possible a value similar to that of the high-intensity beam, while the vertical one should be similar to that of the pencil beam used for the phase space measurement. The first requirement allows reproducing the conditions achieved when operating with an intense beam, while the second one allows reducing the nonlinear horizontal/vertical coupling, thus facilitating the setting-up during the first attempts.

During this stage of the measurements the key instrument is the wire scanner [16]: it allows recording the horizontal beam profile, thus showing the details of the splitting. Examples of profile measurements can be seen in Figs. 5, 6, 8, 9. The raw data are fitted using five Gaussian distributions whose mean, sigma, integral, are assumed to reflect the properties of the beamlets.

<u>Trapping measurement with a high-intensity beam</u>. This represents the most important test for this novel approach. The best result achieved is shown in Fig. 5, where the intensity as a function of time is shown in the upper part. The injected intensity is slightly above 6×10^{12} protons and small losses are visible up to transition crossing (at about 400 ms). Then, the intensity stays remarkably constant up to extraction, which is performed by means of a kicker in a single turn after having merged back the beamlets to reduce the beam size in the horizontal plane to match the septum acceptance. In the lower part of Fig. 5 the beam profile after the splitting is shown. A number of peaks are visible; in particular the central one features rather large

tails. Indeed, the left tail is due to the projection of the beamlet behind (see Fig. 2, right). Another important point is that the left-most beamlet is very well-separated and the region between it and the central core is depleted. This feature is crucial for having small or no losses at all at extraction, as it guarantees no interaction between the extraction septum blade and the beam.

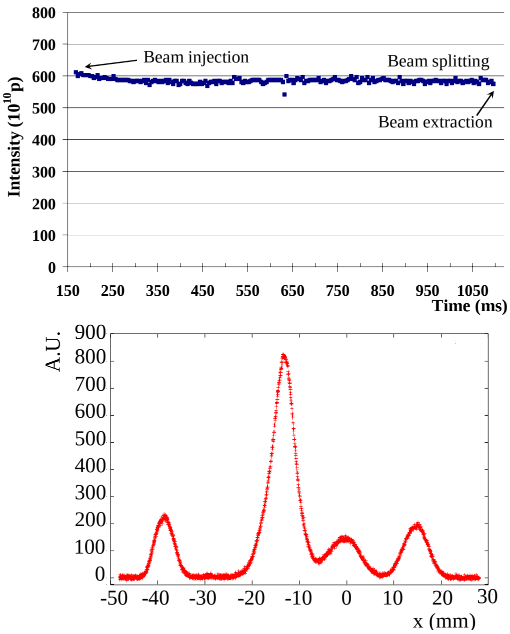

Figure 5: Best result achieved with a high-intensity beam, whose intensity as a function of time (upper) and horizontal beam profile at the end of the capture process (lower) is shown. The profile is not centred at zero due to an instrumental offset of the wire position.

A final test was performed to increase the fraction of particles trapped inside the islands. For this study, a special setting of the octupoles was programmed: instead of keeping their strength constant all over the resonance-crossing phase, the current was suddenly increased just before resonance crossing and then gradually reduced. This should generate large islands at small amplitudes, thus trapping more particles from the region where the density is high, and then keeping almost constant the island's size. The results are shown in Fig. 6, where the measured horizontal beam profile is shown.

Under these new conditions it was indeed possible to increase the fraction of particles inside the islands, achieving a value of 18 % with respect to the total beam intensity against a previous value of about 13 %. It is worthwhile mentioning that for the optimal performance of the SPS machine, the allowed fraction of particles inside each beamlets is limited to (20±5) %: if this holds for the central core, the limit for the other beamlets is instead (20±1) %. However, the price to pay was the presence of slightly higher losses during resonance crossing up to the level of 2-3 % of the total beam intensity.

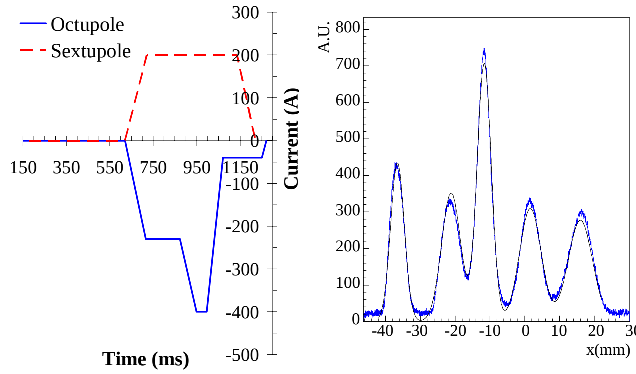

Figure 6: Typical time-dependence of the sextupole and octupole strengths used in the experiment (left). The horizontal beam profile after splitting is shown for the case of the largest fraction of trapped particles (right). The profile is not centred at zero due to an instrumental offset of the wire position.

As a final result the beam distribution as measured in the transfer line downstream the extraction point from the PS machine is shown in Fig. 7. An Optical Transition Radiation (OTR) [18] is used to record the two-dimensional beam distribution in physical space.

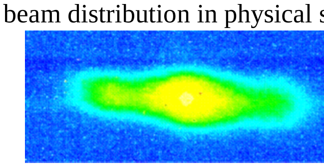

Figure 7: Two-dimensional beam distribution in physical space of the split beam in the transfer line downstream of the PS extraction point.

The peculiar shape of the beam distribution is clearly visible: the two lateral peaks represent the projection in the physical space of the beamlets.

The main parameters of the single-bunch beams used in the experimental campaign are summarised in Table 1.

Table 1: Parameters of the three single-bunch beams used for the experimental tests of the novel multi-turn extraction. The emittance is the normalised, one sigma value.

Parameter	Intensity (protons/b)	$\varepsilon^*_{H/V}(\sigma)$ (μm)	$\Delta p/p(\sigma)$ 10^{-3}
Low-intensity, pencil beam	5×10^{11}	2.3/1.3	0.25
Low-intensity, large horizontal emittance	5×10^{11}	6.2/1.6	0.25
High-intensity beam	6×10^{12}	9.4/6.4	0.60

Special Measurements

In addition to the measurements performed to establish the feasibility of the proposed method, a number of detailed measurements were performed to study the dependence of the beamlets parameters, such as fraction of captured particles, position, width, on the nonlinear parameters and, what is even more important, on the way

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the resonance in crossed. Although in the numerical simulations the influence of a polynomial dependence on the turn number of the linear tune was tested [2, 3, 4], in the real experiments only a linear tune variation was tested. However, the influence on the resonance crossing speed was assessed.

During such a test the resonance was crossed twice with the aim of bringing back the beamlets towards the central core. In case the resonance crossing is slow enough, one could argue that it should be possible to end up in a state not too different from the initial one. The crossing speed was the same in both directions and after the first resonance crossing, the tune was kept constant for a period of 20 ms or 180 ms. The horizontal beam profile was measured at three different moments: before the first resonance crossing, after the first resonance crossing when the tune was constant and the beam split, after the second resonance crossing. The crossing speed is changed and the profiles for many values of the crossing speed recorded.

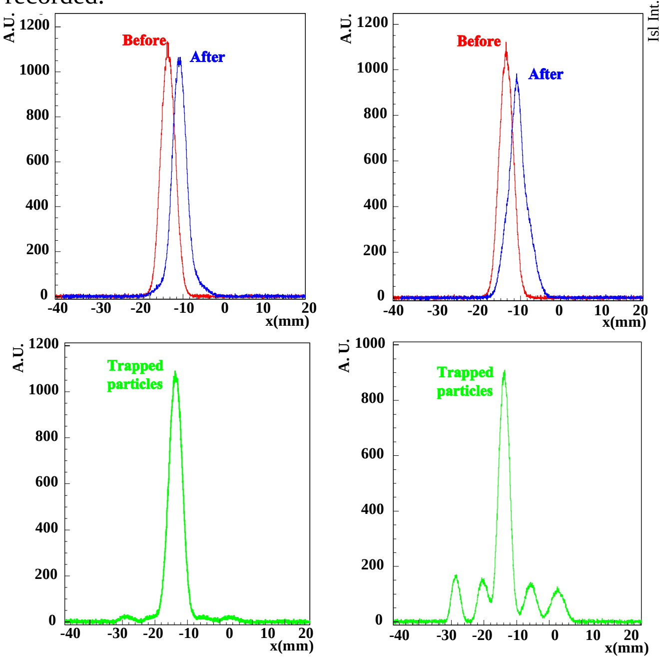

Figure 8: Dependence of the beamlets parameters on the resonance crossing speed. The horizontal profiles for a fast crossing (5 ms) are shown in the left part, corresponding to the three moments, while the profiles on the right correspond to a slower crossing (90 ms). The profiles are not centred at zero due to an instrumental offset of the wire position.

When a fast crossing occurs, almost no particles are trapped inside the moving islands and the final profile resembles very much the initial one. On the other hand, when a slow crossing occurs, many more particles are trapped inside the islands, but the final beam profile is no more Gaussian and differs from the initial one. The hypothesis is that the tails are generated by the beamlets when they are put back into the central core. As long as the crossing time is longer than 30-40 ms the fraction of particles trapped inside the beamlets stays constant and the final profile features non-Gaussian tails. The situation does not change quantitatively in case the period when the tune is kept constant is reduced drastically: the process seems to be always non-reversible.

The influence of the octupole strength on the number of particles captured in the islands is the last example of detailed measurement presented in this paper. The maximum negative current corresponding to the second plateau shown in Fig. 6 (left) is changed. The influence of the octupole is twofold: it changes the islands' size and it varies the detuning with amplitude, thus moving the islands' centres. In Fig. 9 the results are shown.

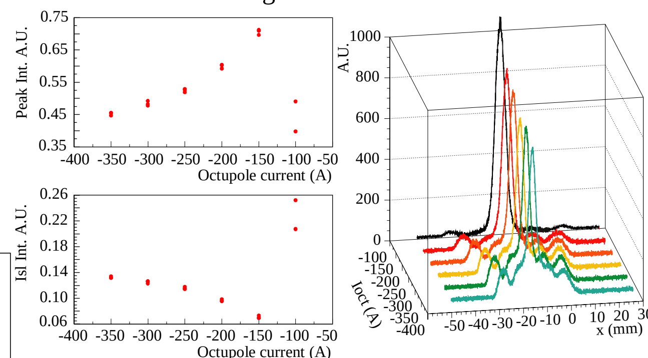

Figure 9: Influence of the octupolar strength on the fraction of particles trapped in the beamlets (upper left) with respect to the intensity in the central core (lower left). The corresponding horizontal beam profiles are also shown (right part).

The increase of the number of particles trapped when the strength of the octupole is reduced is clearly visible (upper left). At the same time, the fraction of particles remaining in the central core is reduced (lower left). Two points are clearly outliers: the fit procedure failed for those two cases because of the too low intensity captured in the islands. The horizontal beam profile measured at the end of the splitting process is shown in Fig. 9 (right). The impact of the octupole on the fraction of particles trapped, as well as on the position of the beamlets is clearly visible.

TOWARDS AN OPERATIONAL VERSION OF THE MULTI-TURN EXTRACTION

The experimental campaign was completed by the end of the year 2004. During the long shut-down of the PS machine, which will be re-started in spring 2006, the analysis of the required changes to implement the proposed multi-turn extraction will take place. The main modifications to the PS ring will involve a new layout of the slow bump used to approach the beam to the extraction magnetic septum and a new fast, closed-bump around the extraction septum. As far as the fast closed-bump is concerned, it will be generated by means of kicker magnets, which will have to be built in the next years. A crucial issue is the available aperture, as the situation is particularly critical in the extraction region. Due to the very principle of the novel multi-turn extraction, once the beam is split, there will be five beamlets circulating in the ring with different closed-orbits.

The closed bumps, both the slow and the fast one, will affect differently the closed-orbits of the five beamlets and the aperture should be large enough to accommodate all beamlets simultaneously without losses.

A Study Group was set-up since 2003 [19] with the mandate to study the theoretical, experimental, and implementation aspects of the proposed multi-turn extraction. Its activities were prolonged in 2004 and the conclusions will be published in spring 2005.

The details of the installation schedule are not known, yet. However, tests with beam will be resumed in 2006 to study how to reduce the losses observed during resonance crossing when the fraction of particles captured inside the beamlets is increased. By 2007 the new layout of the slow bump should be operational, while the fast bump should be installed and commissioned in 2008 at the latest. Therefore, the commissioning of the proposed multi-turn extraction will take place in 2008. During that year, it is foreseen to leave in operation the hardware related with the present CT extraction, to allow delivering beam to the CNGS experiments, while commissioning the novel multi-turn extraction. Finally, upon completion of this crucial stage, the CT will be decommissioned and the novel multi-turn extraction will be the only mean to deliver beam to the CNGS experiments as well as to the other fix target experiments at the SPS.

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