MULTITURN EXTRACTION BASED ON TRAPPING IN STABLE ISLANDS AT CERN PS: RECENT MEASUREMENT ADVANCES

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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. During the year 2002, preliminary measurements at the CERN Proton Synchrotron with a low-intensity, single-bunch, proton beam, confirmed the possibility of generating various beamlets starting from a single Gaussian beam. The experimental campaign continued also during the year 2003 to assess a number of key issues, such as the feasibility of trapping with high-intensity beam and capture efficiency. The experimental results are presented and discussed in detail in this paper.

INTRODUCTION

Since the approval of the CERN Neutrino to Gran Sasso Project (CNGS) [1] and the consequent efforts devoted to a feasibility study of an intensity upgrade of the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS) complex [2], the special extraction mode, the so-called Continuous Transfer (CT) [3], was reviewed. Such and extraction scheme is required to minimise the filling time of the SPS at 14 GeV/c, while reducing the beam emittance so to overcome the aperture limitations at SPS injection. The CT extraction was developed in the seventies [3] with the aim of extracting the beam from the PS in five consecutive turns using an electrostatic septum to slice the beam in the horizontal plane, the tune being 6.25. The main drawbacks of this technique are the intrinsic losses on the electrostatic septum and the poor betatron matching of the five slices, which might transfer into injection losses in the SPS [4].

Recently, an alternative method was proposed, where the beam is split in the transverse phase space by means of adiabatic capture inside stable islands of the fourth-order resonance [5]. The method was then generalised by using other stable resonances [6].

On the experimental side, intense efforts were devoted to the demonstration of such a novel technique since the year 2002, when beam splitting was observed using a low-intensity single-bunch beam [7]. However, the key issue, i.e. whether the method would work for a high-intensity bunch, was still answered and it was tackled during the 2003 PS run (see Ref. [8] for a detailed account on the achievements of this study).

MEASUREMENT CAMPAIGN

Machine and Instrumentation

The stable islands are generated by means of sextupoles and octupoles. Following the experience gained in the previous year, two sextupoles have been installed in section 55 to complement those in section 21: the two sets are mutually exclusive, being powered by one single power converter. The two octupoles are located in section 20. It is worthwhile mentioning that the PS lattice features the minimum of β_H in even straight sections. A sketch of the PS circumference together with the key elements used in the experiments is shown in Fig. 1.

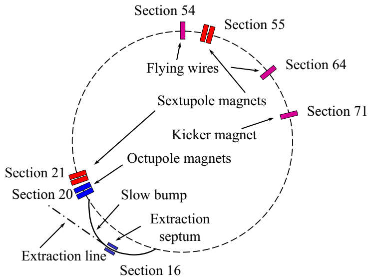

Figure 1: Layout of the PS machine including the key elements for the test of adiabatic capture.

Phase space reconstruction and beam profile measurements are the techniques applied in the experimental study. The first ensures that the right phase space topology is generated with the nonlinear magnetic elements, while the latter is meant to record the evolution of the beam distribution during the trapping process and other beam manipulations. The phase space reconstruction is based on turn-by-turn acquisition of the beam trajectory on two pickups $90°$ apart [7]. The beam profile is measured by means of a wire scanner [9]. Among the four installed, two for each transverse plane, the horizontal one in section 54 is routinely used for the measurements reported here. The profile is reconstructed by means of a scintillator detecting the secondary particles generated by the beam-wire interaction. As the scintillator was originally located on one side of the vacuum chamber, in the median plane, the final beam profile featured an unphysical left/right asymmetry (see Fig. 3). This effect was solved by placing the scintillator at the bottom of the vacuum pipe, on-axis (see Figs. 4, 5).

Each measurement type requires a dedicated beam, which differs in intensity and transverse emittances. All beams are made by a single bunch. A summary of beam parameters is reported in Table 1.

Comments	Int. (10^{10})	$\epsilon^*_H(\sigma)$ (μm)	$\epsilon^*_V(\sigma)$ (μm)	$\Delta p/p(\sigma)$ (10^{-3})
pencil beam	40	1.7	1.55	0.25
low-intensity	45	9	2.38	0.25
high-intensity	600	13.2	7.6	0.6

Table 1: Main parameters of the beams used for the studies. The value of $\Delta p/p$ refers to 14 GeV/c and $\epsilon^*_{H,V}(\sigma)$ stands for the normalised rms emittance.

Phase Space Measurement

The low-intensity pencil beam is normally used for space space reconstruction to avoid as much as possible beam filamentation. The beam trajectory is perturbed by a kicker magnet (notably the one normally used to fast extract the beam) and betatron oscillations are observed on two pickups 90° apart. The standard choice for the pickups is to select those in section 63 and 67. An example of phase space measurement with a clear signature of stable islands is shown in Fig. 2. The four spots indicate the islands' position. Oscillations of the beam position right after the kick indicate that the beam is rotating around the island's centre and filamentation occurs until such oscillations are completely damped. The slow variation over time of the islands' position is very likely due to particles' diffusion outside the islands induced by longitudinal motion. A detailed analysis of the phase space measurements can be found in Ref. [10].

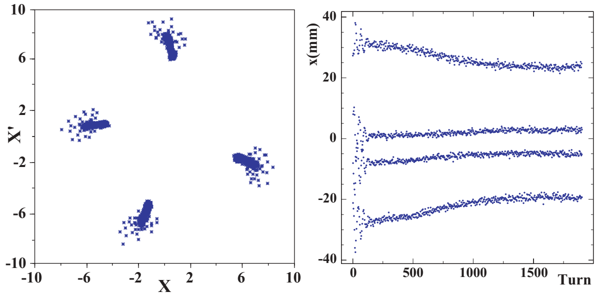

Figure 2: Measured horizontal normalised phase space at section 63 (left) and beam position vs. time (right) for the pickup in section 63.

Adiabatic Capture of Low-Intensity Bunch

The first step in the proof of principle of the novel multi-turn extraction is the adiabatic capture of a low-intensity beam. This requires a beam with a large horizontal emittance, so to simulate the high-intensity beam, and a small vertical emittance to ease the measurement by avoiding nonlinear coupling between the two transverse planes. A typical result of the adiabatic trapping with a low-intensity beam can be seen in Fig. 3, where the horizontal beam profile is shown for three values of the final tune. This shows clearly that, by varying the value of the final tune after crossing the fourth-order resonance, it is possible to change the beamlets' separation. Furthermore, particles are completely removed from the regions between the beamlets [7]. No particles' loss occurs during the capture and transport process. The actual shape of the final beam profile is a result of a projection effect combined with the islands' phase at the location of the wire scanner.

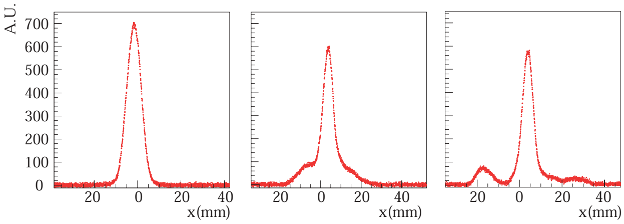

Figure 3: Horizontal beam profile measured by the wire scanner for three values of the tune. The unphysical left/right asymmetry is clearly visible.

In the proposed approach for multi-turn extraction the aim of adiabatic capture is two-fold: first it should split the beam in the horizontal plane so to generate a series of well-separated beamlets; second, it should allow reducing the horizontal emittance of the generated beamlets with respect to that of the circulating beam. In this respect emittance conservation and adiabaticity conditions are critical issues. To this aim a series of measurements were performed to assess the actual reversibility of the process. By crossing the resonance twice, so to split the beam and merge it back, with different values of the crossing time Δt (see Fig. 4 upper left), horizontal beam profiles were taken before and after the manipulation to determine whether the initial beam profile was restored. In Fig. 4 (upper right) typical beam profiles are shown. The final stage is represented by the superposition of two Gaussian functions, the second one much larger than the central peak and with tails heavier than a standard Gaussian. The results are shown in the lower part of Fig. 4, where the rms of the raw data is plotted together with the so-called halo parameter [11]

$$h = \frac{< x^4 >}{< x^2 >^2} - 2, \qquad (1)$$

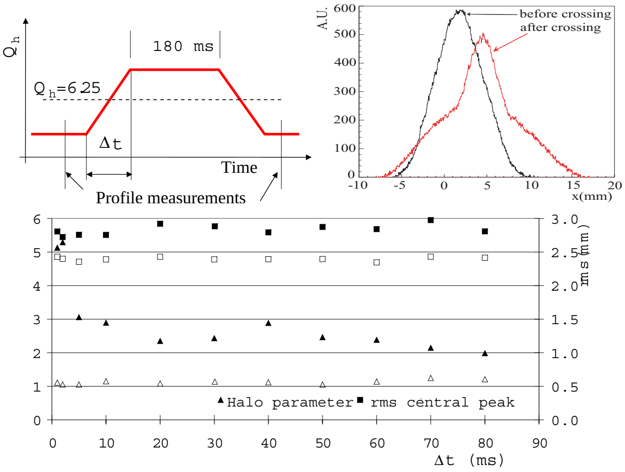

Figure 4: Tune manipulation for the reversibility tests (upper left). Typical beam profiles for reversibility tests (upper right). The unphysical left/right asymmetry is clearly visible. Results of the reversibility tests: the halo parameter and the rms of central peak vs. Δt (open markers: before crossing, full markers: after crossing).

where $< x^n >$ is the nth central moment of the beam profile, $h = 1$ for a Gaussian profile, and $h > 1$ when tails heavier than Gaussian are present. The rms of the central peak is almost unchanged by the double resonance crossing, while the halo parameter shows a significant variation vs. Δt, indicating that the initial profile is Gaussian, while the final one tends to be Gaussian the longer the time to cross the resonance. These results seem to indicate that the process is not reversible, possibly due to phenomena like tune ripple.

Adiabatic Capture of High-Intensity Bunch

The most difficult part was the capture of a high-intensity bunch of similar characteristics as those required for the proposed intensity upgrade for the CNGS [2]. Indeed, adiabatic trapping conditions were succsessfully established even for a bunch of intensity up to 6.25×10^{12} protons (the nominal intensity being 6×10^{12} protons). An example of the beam profile at the end of the capture process is shown in Fig. 5 (left), where the two cases, i.e. nominal and record intensity, are plotted. Contrary to the low-intensity case, about 20 % of the total beam is lost at the end of the capture process. This effect might be induced by the strong vertical perturbation generated by the octupoles located at a high-β_V section, which is imposed by mechanical constraints. As a result, the assumption concerning the decoupling of the two transverse planes is broken.

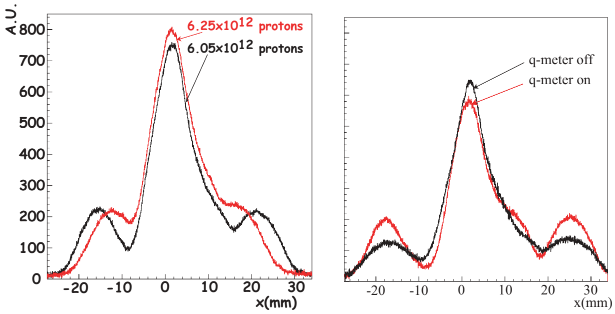

Figure 5: Left: horizontal beam profiles for nominal (black) and record intensity (red). For the latter case, the beamlets separation was reduced to decrease beam losses. Right: horizontal beam profiles for nominal intensity with (red) and without (black) beam perturbation. The unphysical left/right asymmetry is solved in both cases.

For the novel approach to be a viable replacement for the CT extraction, the five beamlets should have approximately the same intensity. However, this is not the case and the issue of increasing the fraction of particles trapped inside the beamlets was considered. In Fig. 5 (right) the beam profile at the end of the adiabatic capture is shown for the nominal intensity and the standard resonance crossing as well as for a special case where the beam is kicked by means of the q-metre kicker when crossing the resonance. The beneficial effect, in terms of fraction of particles in the beamlets, is clearly visible. The q-metre induces a small, but not negligible core-emittance blow up, resulting in a higher particle density in phase space regions where the islands have a finite size, thus increasing the fraction of particles trapped inside.

CONCLUSIONS AND OUTLOOK

The 2003 experimental campaign confirmed the positive results obtained in 2002 with a low-intensity single-bunch proton beam, including also more refined measurements on the reversibility of the process. In addition, tests with a high-intensity beam (6×10^{12} protons) were performed showing that adiabatic trapping is indeed possible and that a controlled core-emittance blow- up can increase the capture efficiency. However, contrary to the low-intensity case where no losses are observed, about 20 % of beam is lost by the end of the trapping process. A possible explanation might be the location of the strong octupoles in a high-β_V section, inducing a strong nonlinear coupling. During the shutdown 2003/2004 the octupoles were replaced with another magnet fitting the aperture requirements of a low-β_V section. Further studies are planned during the whole 2004 PS run to assess whether the proposed approach is indeed a viable replacement of the present CT extraction for the high-intensity CNGS beam.

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