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REPORT OF THE STUDY GROUP ON THE NEW MULTI-TURN EXTRACTION IN THE PS MACHINE

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Abstract

Since the year 2001 considerable efforts were devoted to the study of a possible replacement of the Continuous Transfer (CT) extraction mode from the PS to the SPS. Such an approach is based on the use of stable islands of phase space, generated by sextupoles and octupoles, to capture the beam inside, thanks to a properly chosen tune variation. Both numerical simulations and measurements with beam were performed to understand the properties of this new extraction mode. Recently, a Study Group was set-up with the mandate of studying this novel extraction in view of using it as a replacement for the CT, as well as technical issues related with this approach. The results of the analysis carried out so far, and the conclusions of the Study Group are presented and discussed in this report.

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1 Introduction

In the framework of the activities to prepare the future high-intensity proton beam for the CERN Neutrino to Gran Sasso (CNGS) Project [1], a critical review of the key processes used to generate such a beam was carried out [2], in view, possibly, of an upgrade beyond the present nominal intensity value of about 3.3×10^{13} protons per PS batch.

Among other issues, efforts have been devoted to the improvement of the present extraction scheme from PS to SPS, the so-called Continuous Transfer (CT). Such an extraction mode was developed in the mid-seventies [3] with the aim of delivering a beam to the SPS five PS turns long and with a reduced horizontal beam emittance to overcome the SPS aperture limitation in the vertical plane: a special optics in the transfer line joining the PS and SPS allows exchanging the two transverse planes (in particular the emittance values) [4]. This approach consists in slicing the beam by means of an electrostatic septum: with the horizontal tune set to 6.25 this method allows generating one continuous ribbon four-turn long plus an additional slice, represented by the beam core, for a total beam length of five PS turns. Although this extraction mode is certainly adapted to present performance, in the event of an intensity increase, a number of potential weak points appear, such as the intrinsic beam losses related with the underlying principle of this extraction mode, and also the properties of phase space matching of the different slices.

In the framework of the High Intensity Protons Working Group (HIP-WG) [5] a detailed analysis of the losses for the beam for CNGS was performed [6]. The outcome is rather striking: of the overall intensity of about 4.5×10^{19} protons/year required by the neutrino experiments, approximately 1.7×10^{19} are lost in the accelerator chain, corresponding to about 40 % of the total intensity. A large fraction of the beam losses, i.e. 0.7×10^{19}, or 40 % of the total intensity lost, occurs in the electrostatic septum of the PS ring used to slice the beam!

In the quest for an improved extraction mode, a novel approach was proposed. In the new scenario the beam will be separated in transverse phase space by generating stable islands inside the region where the beam sits and by slowly (adiabatically) moving them towards higher amplitudes. By doing this, particles may get trapped inside islands thus generating well-separated beamlets [7, 8]. This method is potentially superior to the present one as no intercepting device is used to split the beam; hence particle losses are limited to the fraction of the beam improperly deflected during the kicker rise time. Furthermore, the extracted beam should better match the phase space structure. Following the encouraging results of the numerical simulations, a measurement campaign on the PS machine was launched in the year 2002 and continued throughout the whole of 2003.

To coordinate these activities, a Study Group was set-up [9] with the following mandate:

- *Demonstrate the feasibility of the scheme*
- *Investigate the various technical issues*
- *Evaluate the resources required to define and specify a possible project to replace the present Continuous Transfer*

The results of the studies performed so far as well as the conclusions of the Study Group are presented and discussed in this report. The plan of the paper is the following: in Section 2 both the CT and the novel extraction are reviewed and compared. In Section 3 the outcome of the measurements performed in the PS machine since 2002 are summarised. In Section 4 the issues still under study are presented, while in Section 5 an estimate of the resources needed to complete these studies, thus specifying a possible project, are presented, and a possible implementation sequence is presented in Section 6. Finally, conclusions are presented in Section 7.

2 Multi-turn extractions at the PS

2.1 The Continuous Transfer

The CT [3] represents the solution to the problem of transferring beam between two machines with different circumferences. In the case of the PS and SPS they satisfy the relation $C_{SPS} = 11 C_{PS}$. Due to the difference in length, to fill the SPS one would require ten fast-extracted pulses from the PS (the empty gap in the SPS is needed for the rise-time of the injection kicker). If the filling time has to be minimised, then the solution consists of extracting the beam over a few turns. In Fig. 1 the layout of the extraction elements is shown together with the horizontal normalised phase space. Just before extraction, the horizontal tune is set to the value 6.25 and the closed orbit is modified so that the blade of an electrostatic septum intercepts the beam. Four slices are shaved off the main core and extracted as a continuous ribbon over four turns. The central part is extracted last, during the fifth turn, by changing the beam trajectory so as to jump over the septum blade. Another interesting property of such an approach is that the horizontal emittance of the extracted beam is decreased with respect to that of the circulating one. However, a number of drawbacks are present, namely: i) beam losses, especially at the electrostatic septum, are unavoidable. They amount to about $15\ \%$[1] of the total beam intensity [10]; ii) the extracted slices do not match the natural structure (circles) of phase space, thus generating a betatronic mismatch. This, in turn, induces emittance blow-up in the receiving machine; iii) the extracted slices have different transverse emittance. A detailed analysis of the properties of the extracted slices can be found in Ref. [11], where computation of the mismatch parameters for the CT as a function of the slicing was performed. For the CT extraction, the optical parameters and the beam emittance are different for the five slices, thus generating different emittance blow-up at SPS injection. Furthermore, due to the fancy shape of the slices, the mismatch can be rather large.

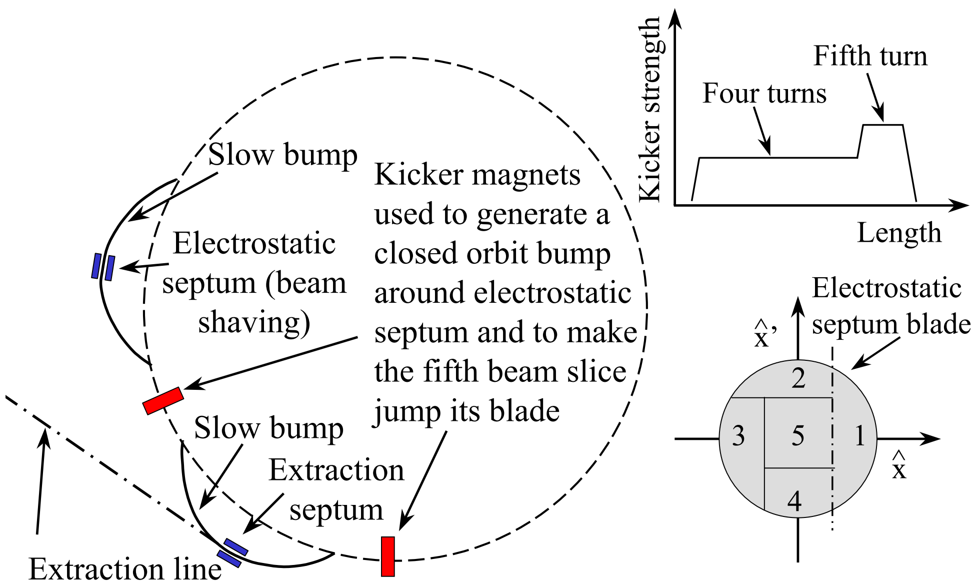

Figure 1: Principle of the CT extraction from the PS machine: the extraction scheme (left), the kicker strength as a function of time (upper right), the normalised phase space (lower right).

2.2 The new multi-turn extraction

In the novel approach [7, 8, 12], nonlinear elements such as sextupoles and octupoles are used to generate stable islands in transverse phase space. Then, by varying the horizontal tune (see Fig. 2 for an

[1] Losses can be reduced down to 10 % or even less, but such performance requires careful and continuous tuning, hence it can be hardly maintained over reasonably long periods.

example), particles can be selectively trapped in the islands by adiabatic capture: some will remain in the phase space area around the origin, while others will migrate to the stable islands. As a result, the

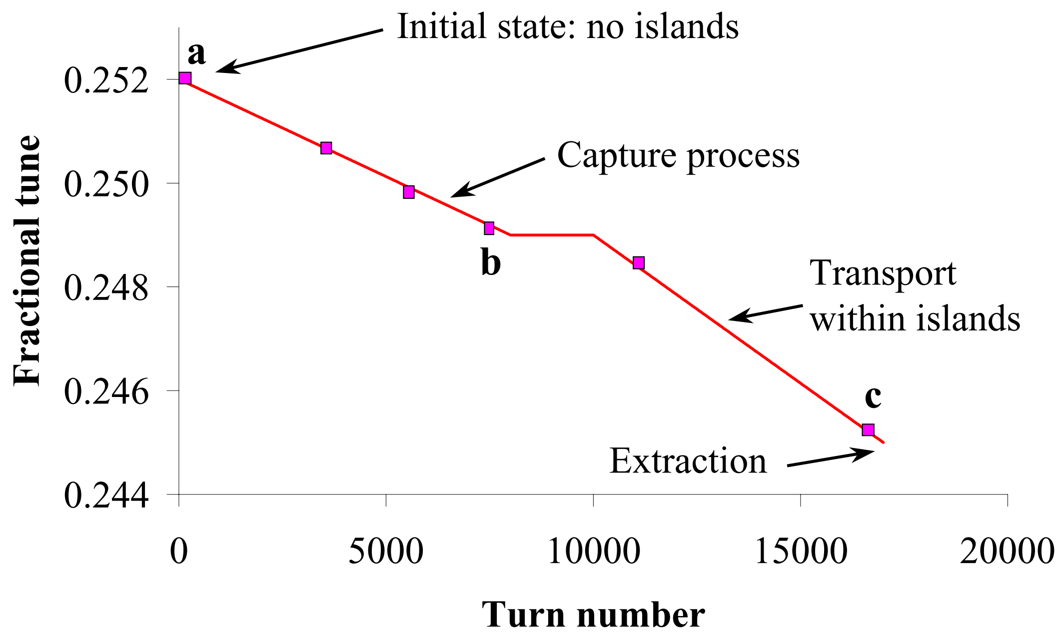

Figure 2: Tune as a function of turn number used for the numerical simulations. The points on the curve labelled with **a**, **b**, and **c** correspond to the values of the tune used to generate the phase space portraits shown in Fig 3.

beam is split into a number of parts in transverse phase space, determined by the order of the resonance used, without any *mechanical* action. Finally, it is possible to move the particles trapped inside the islands towards higher amplitudes. This increases the separation between the different beamlets so that enough room is available for the beam to jump over a septum blade with almost no particles lost. A sequence of phase space portraits, obtained with a simple system, the so-called Hénon map [13], are shown in Fig. 3 to illustrate the whole process.

The final result of a typical capture process inside stable islands is shown in Fig. 4. There, the beam

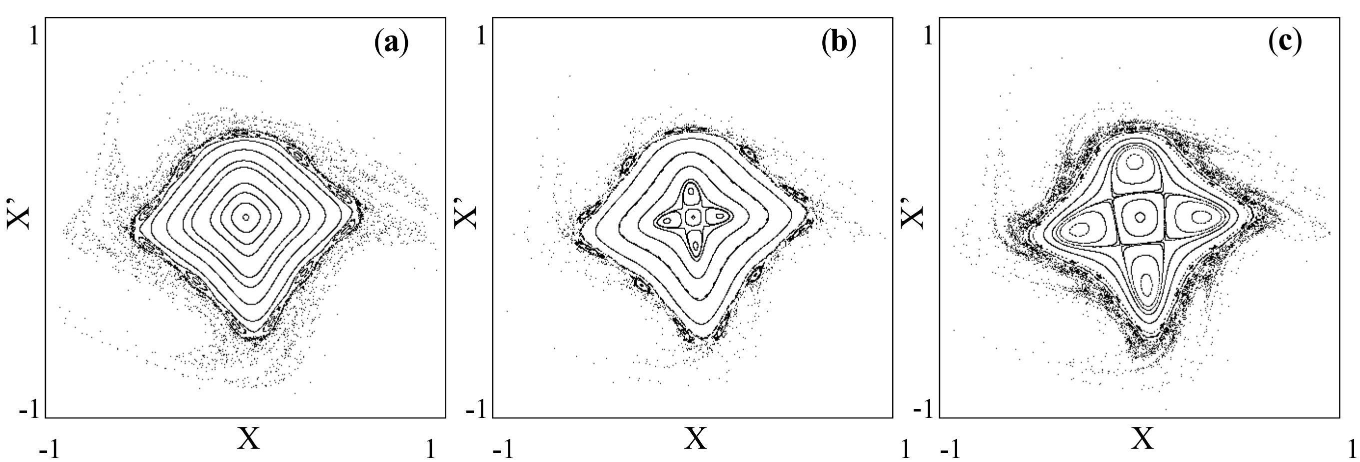

Figure 3: Sequence of phase space portraits obtained for a simple model. The tune values correspond to those labelled with letters in Fig. 2.

distribution as well as its projection is depicted. Although the specific CERN application naturally lead

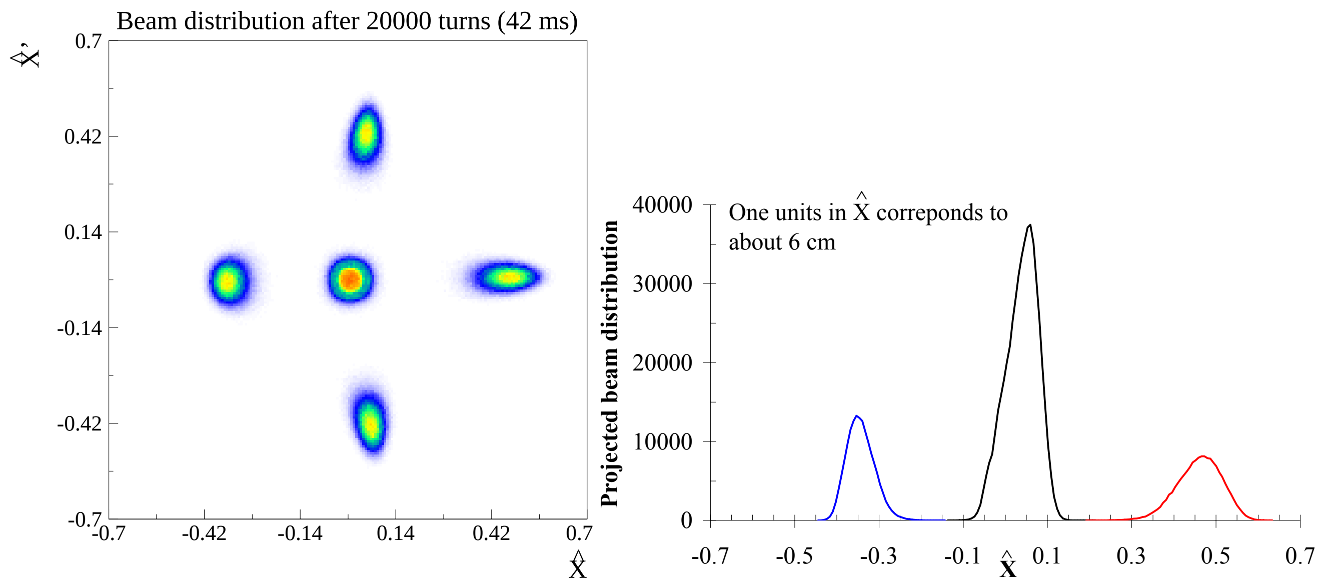

Figure 4: Results of the numerical simulations for the adiabatic capture inside stable islands (left: final phase space distribution, right: projected beam distribution onto horizontal axis).

to study the capture process induced by crossing of a fourth-order resonance, recently it was shown [14] that other resonances, from second- to fifth-order, can be used to design two- or sixth-turn extractions, respectively. Also, by time reversal the approach might be applied for multi-turn injection into a circular machine.

A detailed comparison of the performance of the CT and the novel extraction can be found in Refs. [11, 15]. The new multi-turn extraction does not suffer from the same weak points of the CT. By definition the first four beamlets have exactly the same trajectories, optical parameters, and emittances, due to the fact that the same island generates the properties of the extracted beam. Also, the beamlets' shape match rather well the natural phase space structure (circles), thus inducing small values of the emittance blow-up after filamentation [11]. For the sake of completeness, one has to mention that the novel multi-turn extraction is affected by tune modulation phenomena [16]: any periodic tune-variation might induce islands oscillations, either in angle or in phase depending on the modulation parameters, thus generating emittance dilution in the five beamlets.

3 Results of Machine Development studies

In parallel to simulation studies, many efforts were devoted to experimental tests, also called Machine Development (MD), of the key processes required for the novel multi-turn extraction, namely adiabatic capture, and extraction proper. To this aim sextupoles and octupoles, used to generate the stable islands, were installed in the PS ring, recuperated from the standard magnets in the PS stock. The power converters were recuperated too, being those used to power the Robinson wigglers, which are no more used in operation since the stop of the LEP machine.

Two octupoles were installed in section 20, connected in series, during the shutdown 2001/2002. Their reduced horizontal aperture, imposed to locate them in a section with minimum horizontal beta-function. Among all useful straight sections, section 20 has the nice property of being outside the closed bump generated by kicker magnets between sections 21 and 9. Such a bump is used for the present CT and was supposed to be applied also for the test of the novel multi-turn extraction.

Two sextupoles were installed in section 21, connected in series, during the shutdown 2001/2002. Following the results of the measurements performed during the 2002 run, showing that the phase of the four islands is not optimal at the electrostatic septum, a second set of two sextupoles was installed in section 55 during the shutdown 2002/2003. A single power converter is used to power both sets of sextupoles: a manual switch allows selecting the desired couple of magnets.

As far as the beam instrumentation is concerned, the existing flying wire scanners [17] installed in the sections 54 and 64 (horizontal plane) and in sections 75 and 85 (vertical plane) are the key instruments to measure the evolution of the beam profile during the capture. To reconstruct the phase space topology, thus ensuring the presence of the islands required for the beam capture, a dedicated system for multi-turn acquisition of the beam trajectory, was developed [18, 19]: the pick-ups are those of the Closed Orbit Digital Display system (CODD), while the multi-turn acquisition is achieved by means of a fast digitiser plus some special acquisition software [19]. The pick-ups are chosen to be 90° apart in betatronic phase [20] to ease phase space reconstruction. A schematic view of the PS machine including the main elements used in the tests is shown in Fig. 5. Various beams were produced by the PS-Booster

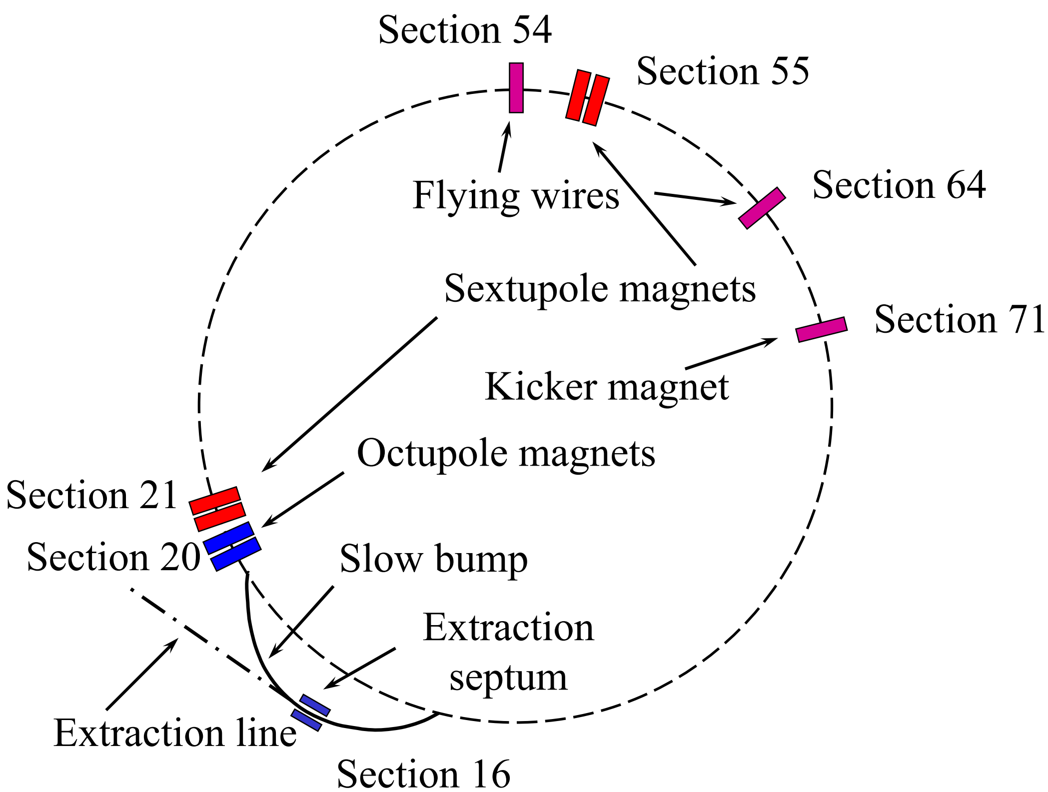

Figure 5: Layout of the PS machine including the key elements for the test of adiabatic capture. Other elements (not shown here) are involved in the final stage of the five-turn extraction.

to fit the requirements of the various tests performed. Single-bunch, low-intensity, pencil beam was used in the phase space measurement campaign. Capture tests began with a single-bunch low-intensity beam having a large horizontal emittance, so to simulate the size of a high-intensity beam, and a small vertical emittance, not too different from the one of the pencil beam. The sieve in front of the PS-Booster is the key device to generate a low-intensity, large emittance beam for the PS-Booster, and it was heavily used both in 2002 and in 2003. This beam was also used in the extraction tests. Finally, a high-intensity, single-bunch beam was produced to test the capture process under realistic conditions, i.e. with the required beam parameters, apart for the number of bunches, for the considered intensity upgrade scenarios for CNGS [2]. A summary of typical beam parameters for the studies presented here is listed in Table. 1.

	Comments	Int. (10^{10})	$\epsilon^*_H(\sigma)$ (μm)	$\epsilon^*_V(\sigma)$ (μm)	$\Delta p/p(\sigma)$ (10^{-3})
2002	pencil beam	40	2	1.5	0.2
	low-intensity capture	50	12	1.8	0.4
2003	pencil beam	40	1.7	1.55	0.25
	low-intensity capture and extraction	45	9	2.38	0.25
	high-intensity capture	600	13.2	7.6	0.6

Table 1: Main parameters for the beams used for the studies of the new multi-turn extraction. The value of $\Delta p/p$ refers to 14 GeV/c. The normalised emittance is defined according to $\epsilon^*_{H/V} = \beta\,\gamma\,\sigma^2_{H,V}/\beta_{H,V}$.

3.1 MDs in the year 2002 [21]

3.1.1 Phase space measurement

The technique used is the standard one, i.e. the beam trajectory is perturbed by means of a kicker magnet (notably the one normally used for fast extraction and installed in sections 71 and 79) and betatron oscillations are observed on two pickups $90°$ apart. To overcome some difficulties due to the islands' phase at the kicker location, two kicks separated by three turns, which is the minimum delay due to hardware limitations, were used, thus allowing to scan along the diagonal in phase space. These measurements are strongly affected by beam de-coherence. In fact, as the beam position monitors measure the centre of gravity of the beam charge distribution, the detected signal fades out after some turns. Special care was taken to minimise such an effect. The choice of using a pencil beam, allows scanning better the phase space structures, also avoiding filamentation in the transverse plane, and hence signal de-coherence. Furthermore, due to the plain FOFDOD structure of the PS lattice, no location with zero dispersion exists, implying that the dedicated sextupoles and octupoles have a strong chromatic effect, leading to a measured value of $\xi_H = {Q'}_H/Q_H \approx 1.7$ and $\xi_V \approx 0.6$. After a careful tuning, the chromaticity was reduced to $\xi_H \approx 0.1$ and $\xi_V \approx 0.9$ (see also Ref. [22] for more details). Furthermore, the rf-voltage was decreased to reduce $\Delta p/p$ (see Table 1 for the numerical value of $\Delta p/p$).

The main results of the phase space measurement campaign are shown in Fig. 6. The various plots refer to different kick amplitudes. In the first portrait, regular motion represented by circular phase space trajectories is visible and signal de-coherence is also apparent. As the kick amplitude is further increased, fourth-fold symmetrical trajectories appear: the beam is kicked inside the stable islands of the fourth-order resonance. A rather strong signal de-coherence is revealed by the curly-shaped beam trajectory, spiralling towards the origin. In principle, particles inside the islands should generate a coherent, albeit small, signal lasting over a long period. The strong de-coherence can be explained by assuming that time-dependent effects make the islands moving in phase space. This is the case when tune ripple is present or when considerable coupling between longitudinal and transverse degrees-of-freedom induce tune modulation via chromaticity. In fact, it turned out that the improvement of the quadrupoles power supplies made it possible to cure completely the problem.

Finally, it is worthwhile pointing out that the results shown in Fig. 6 are in reasonable agreement with the model of the PS machine and with the phase space topology assumed in the numerical simulations [7, 8].

3.1.2 Capture with a low-intensity beam

For the capture tests, the horizontal tune was swept through the fourth-order resonance to induce and observe the trapping phenomenon. The horizontal emittance was increased, by using the sieve at PS-Booster injection, to simulate the size of a high-intensity beam, the other beam parameters being un-

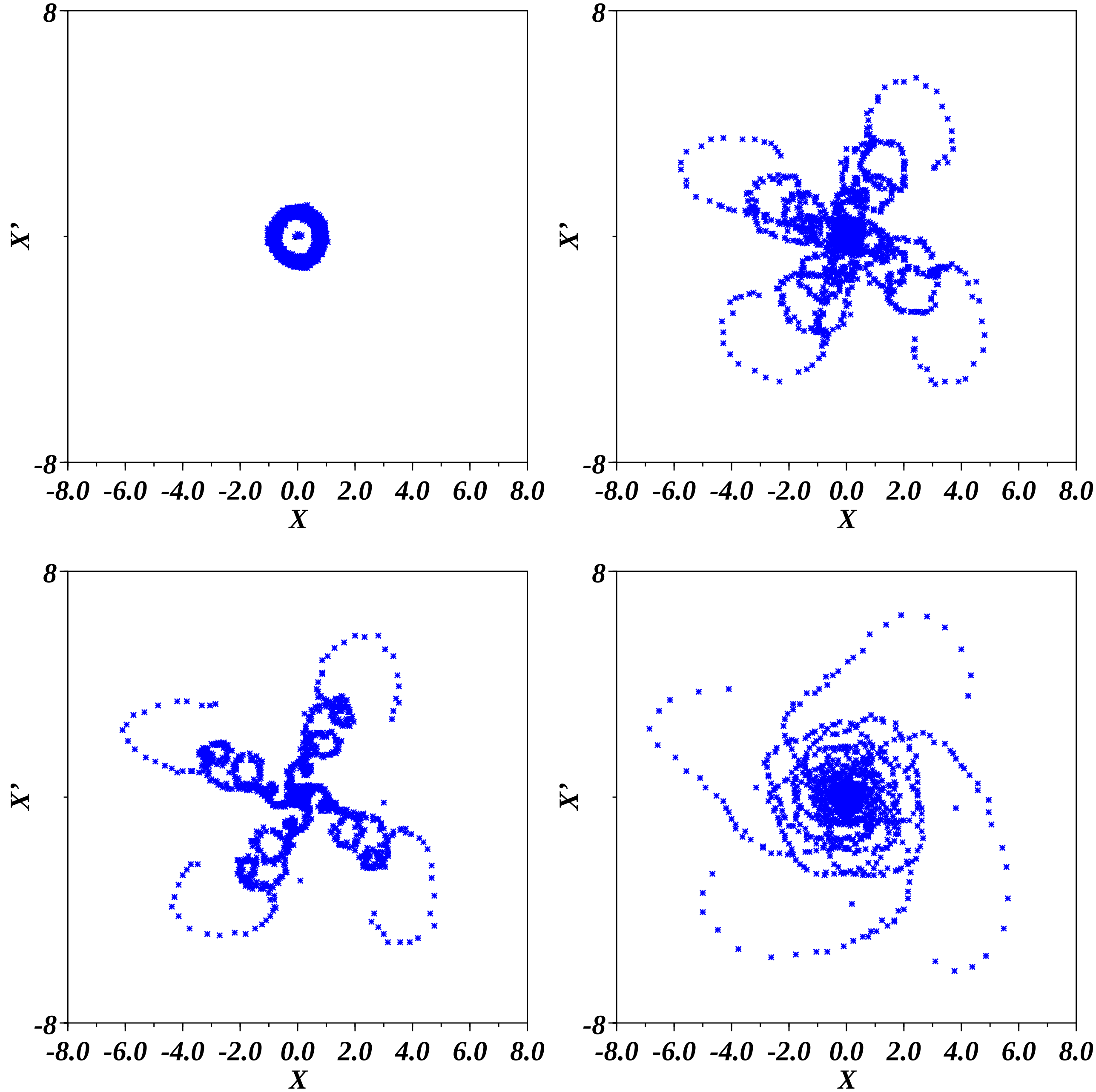

Figure 6: Horizontal normalised phase space measured with the multi-turn system (about 1.9×10^3 turns are plotted, corresponding to about 4 ms) at the location of the pick-up in section 63. The sextupoles used are those located in section 21. Two kicks are applied, separated by three turns.

changed. The experimental conditions are shown in Fig. 7, where the horizontal tune, the strength of the nonlinear elements, and the beam intensity are plotted as a function of time. When the strength of the nonlinear elements levels out, the beam momentum is 14 GeV/c and the magnetic field is constant: the power supplies are rather slow, imposing to start ramping during acceleration. The initial value of the tune is chosen near the fourth-order resonance, then a linear change is applied, during which the capture of beam particles inside islands occurs. The final value of the tune is varied for different beam profile measurements to change the islands' separation. As far as the beam intensity is concerned, some minor losses are visible during the ramping of the nonlinear elements, while during the actual trapping no sign of losses is visible. The main results are shown in Fig. 8, where the beam profile measured by the flying wire scanner is shown for different values of the final tune. The first profile is the reference picture:

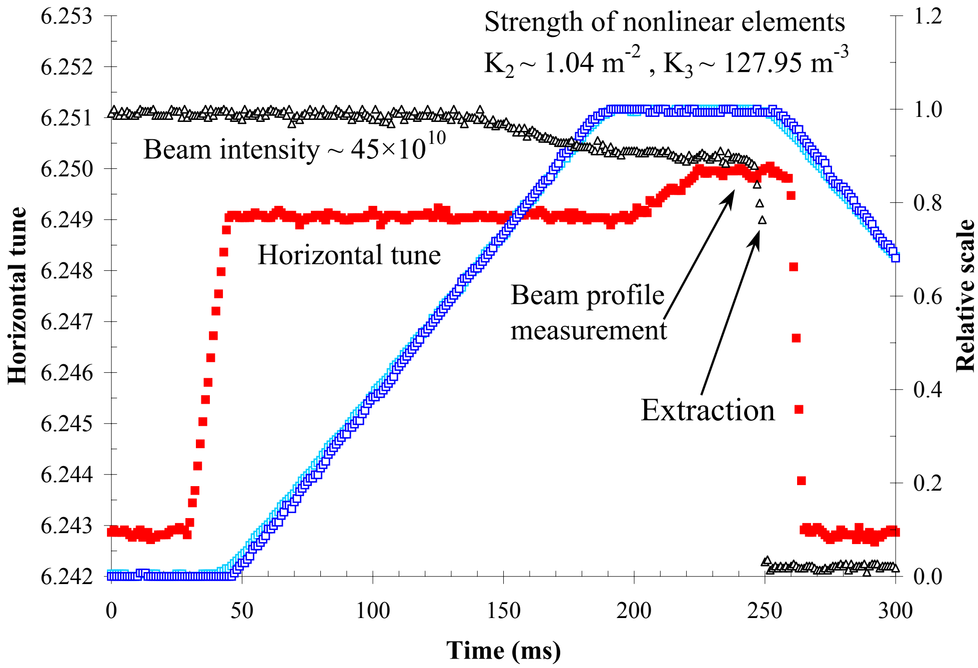

Figure 7: Experimental conditions during the tests for adiabatic capture inside stable islands.

the tune is changed, but as the nonlinear elements are switched off no effect on the beam distribution is visible. The other pictures differ by the value of the final tune: the nonlinear elements are switched on and three additional peaks are clearly visible, whose separation increases as the tune is varied. One should keep in mind that, although the beam is split in five beamlets [7, 8], the wire scanner measures the projection onto the x-axis (see also Fig. 4), therefore, the central peak is higher than the others as it represents the superposition of three beamlets.

In Fig. 9 the horizontal phase space in the presence of the strong nonlinear effects induced by the sextupoles and octupoles used in the tests are shown at different location in the PS ring. The phase of the islands is changing continuously. The phase space portrait have been obtained by tracking a set of initial conditions in the 4D phase space (x, x', y, y') of the form $(A, 0, 0, 0)$ for 500 turns using the measured model of the PS ring at 14 GeV/*c*. The values of the tunes are $Q_H = 6.255$ and $Q_V = 6.30$. The phase at the location of the electrostatic septum is not optimal, as well as that at the location of the kicker, thus explaining the need for scanning along the diagonal in phase space to put the beam inside the islands.

3.2 MDs in the year 2003

3.2.1 Phase space measurement

The installation of the sextupoles in section 55 had a positive impact on the phase space measurements. In fact, the requirement of having the correct, i.e. zero degrees, islands' phase at the electrostatic septum location, automatically imposes the same phase at the location of the extraction kicker placed in sections 71 and 79. Therefore, most of the problems encountered during the campaign of phase space measurement in the year 2002 were overcome as now the bunch can be directly kicked inside the islands, thus generating a clean coherent signal, the characteristic signature of island motion. In Fig. 10 the horizontal phase space in the presence of the strong nonlinear effects induced by the sextupoles and octupoles used in the tests are shown at different locations in the PS ring. The phase space portrait have been obtained by tracking a set of initial conditions of the form $(A, 0, 0, 0)$ for 500 turns using the measured model of the PS ring at 14 GeV/*c*. The values of the tunes are $Q_H = 6.255$ and $Q_V = 6.30$. Contrary to the situation shown in Fig. 9, the islands' phase at the location of the electrostatic septum is now better, as well as the one at the kicker location. As a consequence, the phase space measurements

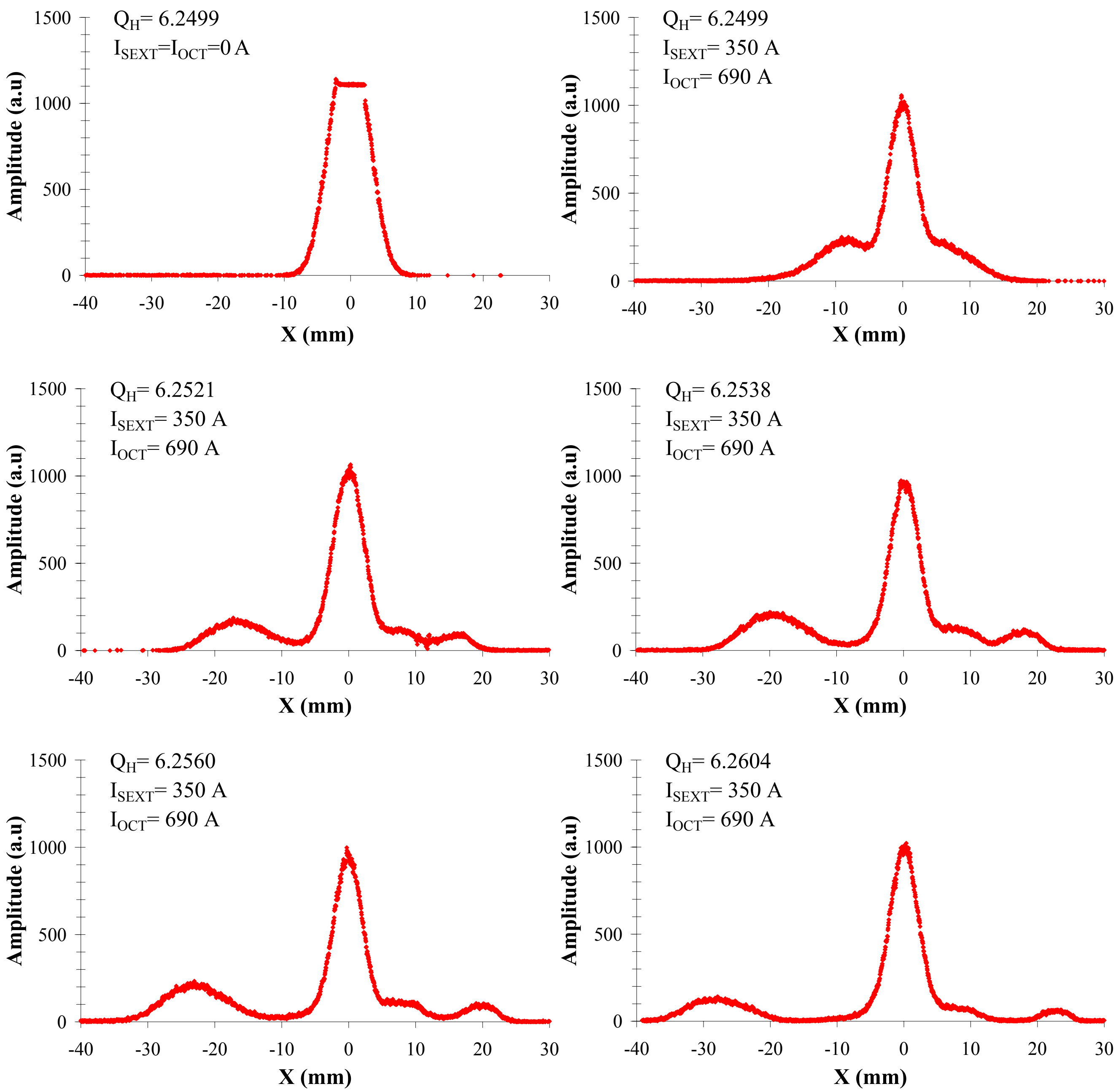

Figure 8: Horizontal beam profile measured by the flying wire scanner located in section 64, for different final values of the tune. The first profile represents the initial beam distribution, when no capture occurs. The choice of the gain, optimised for the subsequent stages of adiabatic capture, explains the signal saturation.

could be performed by simply kicking the beam once, as there was no need for scanning along the diagonal.

The expected improvement was indeed confirmed by measurements. In Fig. 11 a selected number of pictures are shown. The beam is displaced by means of a single kick: due to the correct islands' phase at the kicker location, there is no need to perturb the bunch twice. The transition between the region of regular close curves, and the presence of islands is clearly visible. Islands are now well localised and the spiralling behaviour observed in the year 2002, is not present anymore. In Fig. 12, the time series representing the beam position after kicking the bunch inside the islands as measured by the pick-ups in section 63 and 67 is shown. The initial oscillations indicate that the bunch is kicked somewhat aside the

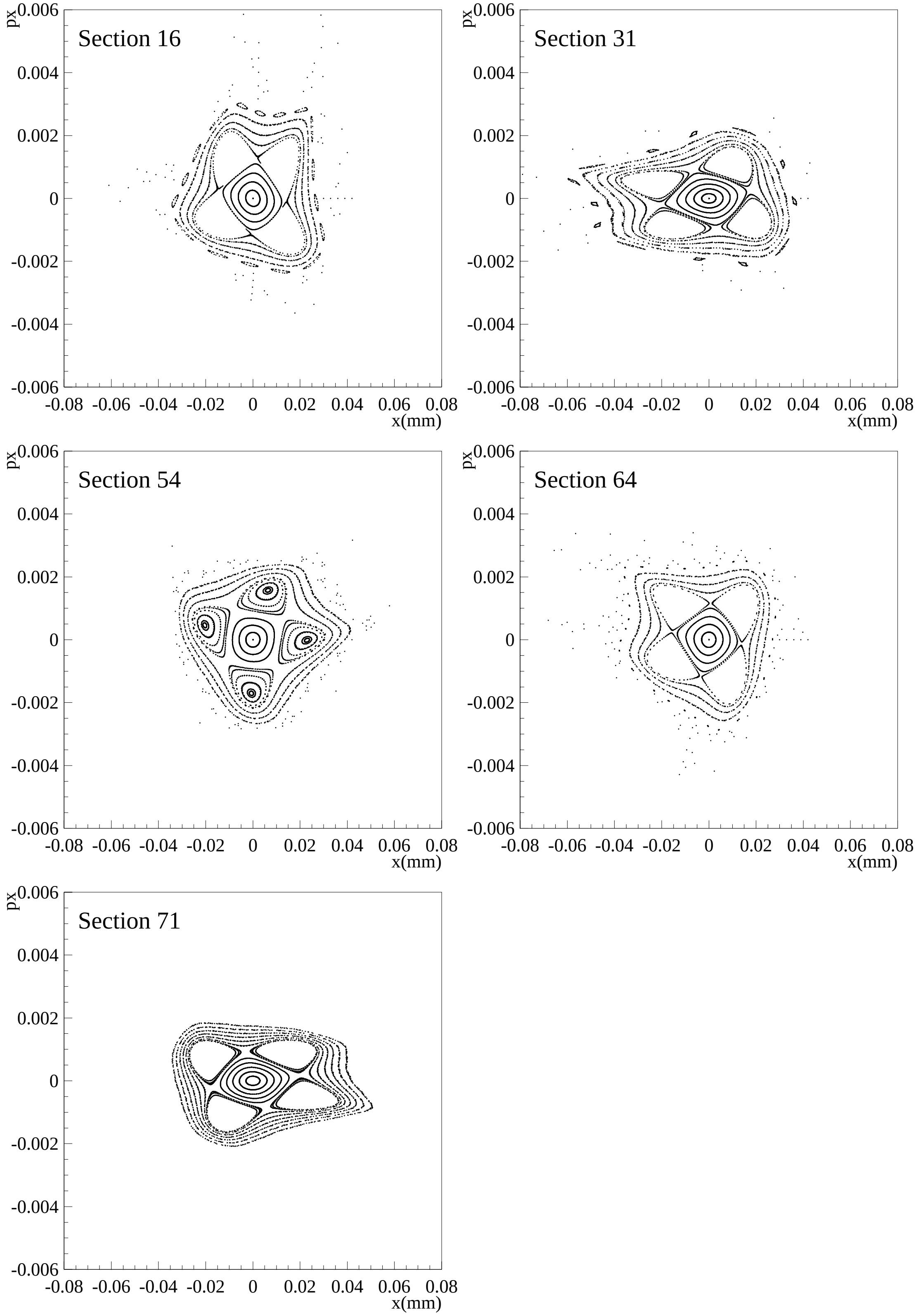

Figure 9: Horizontal phase space portrait in physical coordinates for the conditions used in the experimental tests in 2002. The initial conditions of the form $(A, 0, 0, 0)$ have been tracked for 500 turns. The octupoles are located in section 20 (powered at 690 A) and the sextupoles are in section 21 (powered at 350 A). The tunes are $Q_H = 6.255$ and $Q_V = 6.30$. Different sections of the PS rings are presented here: section 16 (magnetic septum), section 31 (electrostatic septum), section 54 (horizontal flying wire scanner), section 64 (horizontal flying wire scanner), section 71 (extraction kicker used for phase space measurements).

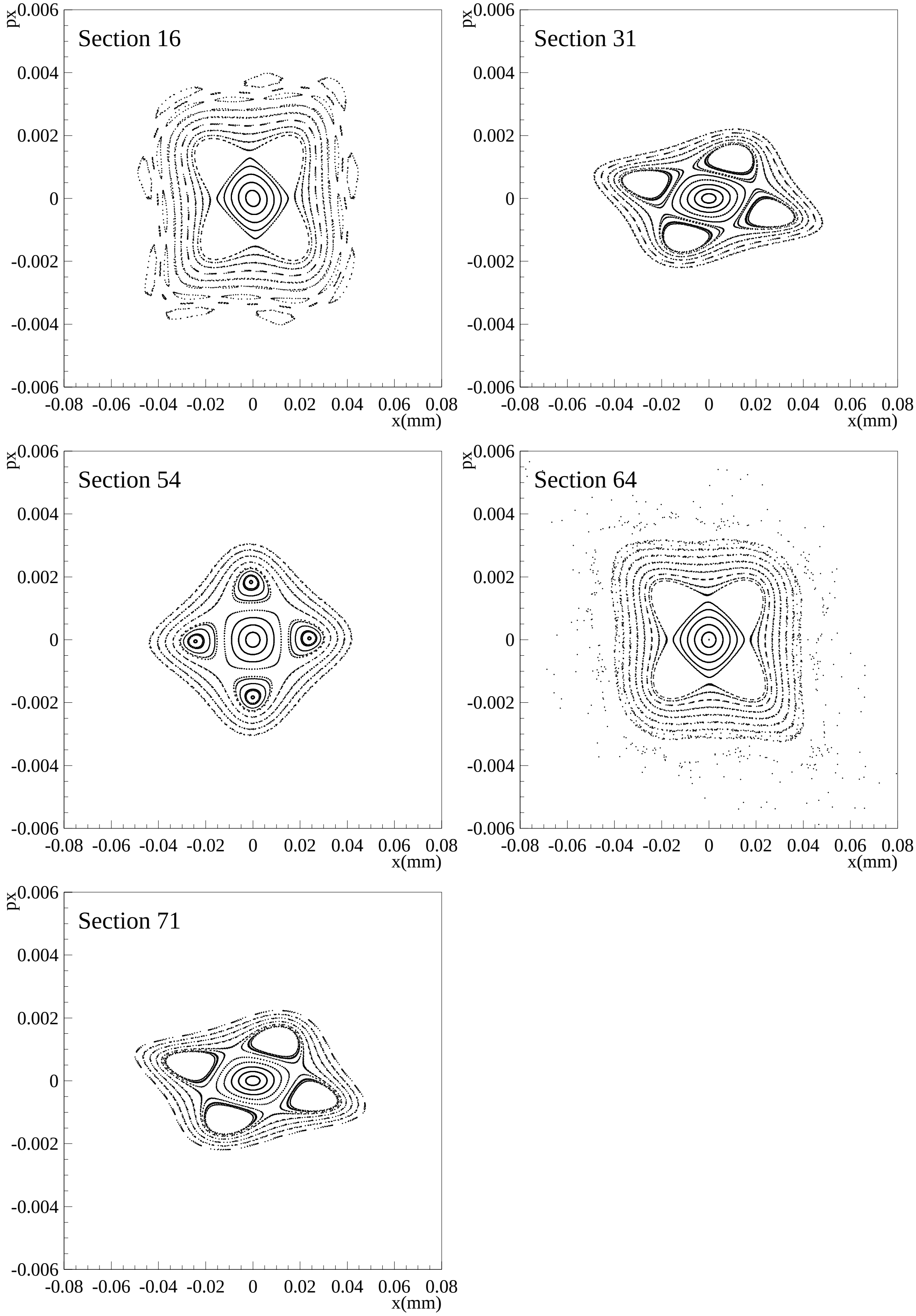

Figure 10: Horizontal phase space portrait in physical coordinates for the conditions used in the experimental tests in 2003. The initial conditions of the form $(A, 0, 0, 0)$ have been tracked for 500 turns. The octupoles are located in section 20 (powered at 690 A) and the sextupoles are in section 55 (powered at 350 A). The tunes are $Q_H = 6.255$ and $Q_V = 6.30$. Different sections of the PS rings are presented here: section 16 (magnetic septum), section 31 (electrostatic septum), section 54 (horizontal flying wire scanner), section 64 (horizontal flying wire scanner), section 71 (extraction kicker used for phase space measurements).

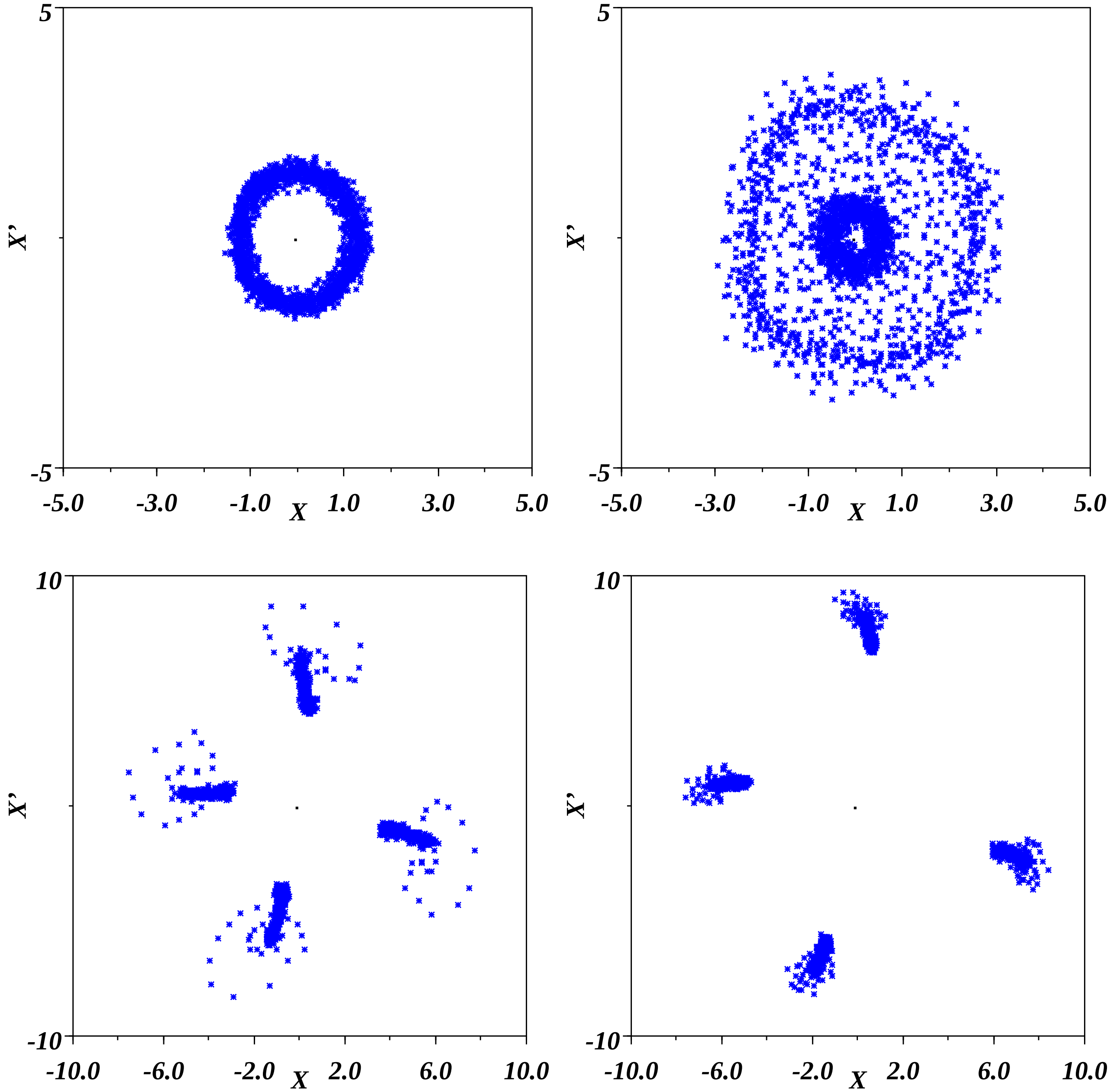

Figure 11: Horizontal normalised phase space measured with the multi-turn system (about 1.9×10^3 turns are plotted, corresponding to about 4 ms) at the location of the pick-up in section 63. The sextupoles used are those located in section 55. One single kick is applied.

island' centre. After few revolutions, the signal is damped due to filamentation. However, a rather large coherent signal is present all along the time span of about 4 ms due to the motion inside the islands.

3.2.2 Capture with a low-intensity beam

Capture tests were repeated also in 2003 using a low-intensity beam. In this case, the islands were generated by means of the octupoles in section 20 and sextupoles in section 55. In spite of the different sextupoles' location, the results confirm the observations made during the 2002 run, namely that well-separated beamlets can be generated by trapping particles inside stable islands. Furthermore, beamlets can be moved towards higher amplitudes without measurable losses. The main results are shown in

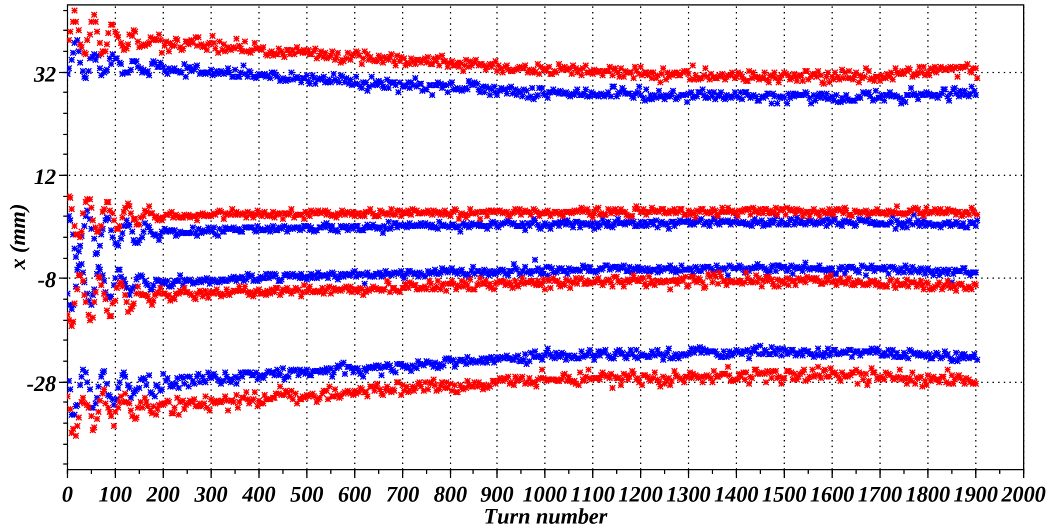

Figure 12: Horizontal beam position as measured by the pick-up in section 63 (red) and in section 67 (blue). Oscillations around the islands' centre are clearly visible at the beginning of the time series. A rather large coherent signal persists for the whole set of about 1.9×10^3 turns (corresponding to about 4 ms).

Figs. 13 and 14. The experimental conditions are essentially the same as for the tests performed in 2002 and reported in Fig. 7. In Fig. 13 the tune evolution in the tune space (Q_H, Q_V) during the capture process is shown. Resonance lines from order 2 to order 10 are also shown. For these tests as well as for

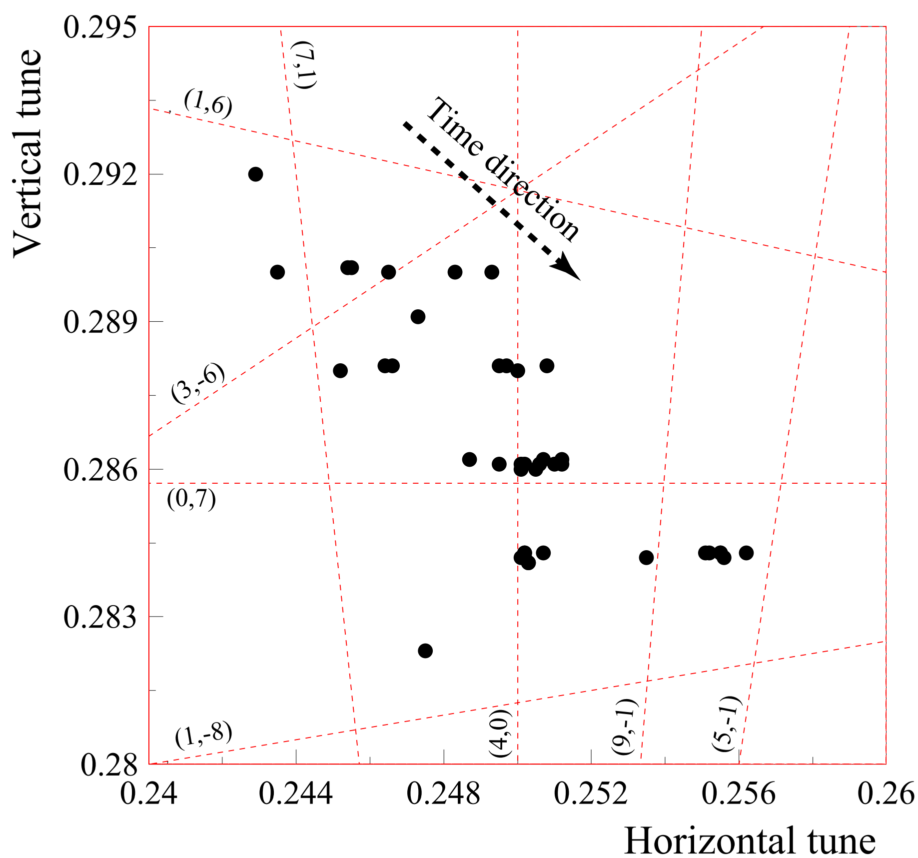

Figure 13: Tune evolution in the tune space (Q_H, Q_V) during the capture process.

those performed in 2002, only the family of focusing quadrupoles, normally used to tune the PS machine at low-energy, was used to change the tune. Therefore, the vertical tune is left floating during the sweep through the resonance. This effect is clearly visible in Fig. 13. In preparation of the capture tests with high-intensity bunch, an alternative method, based on the simultaneous variation of the focusing and defocusing quadrupole families, was implemented with the aim of sweeping through the resonance with Q_H, while keeping Q_V almost constant.

In Fig. 14 the beam distribution after trapping is shown. The four peaks represent the projection

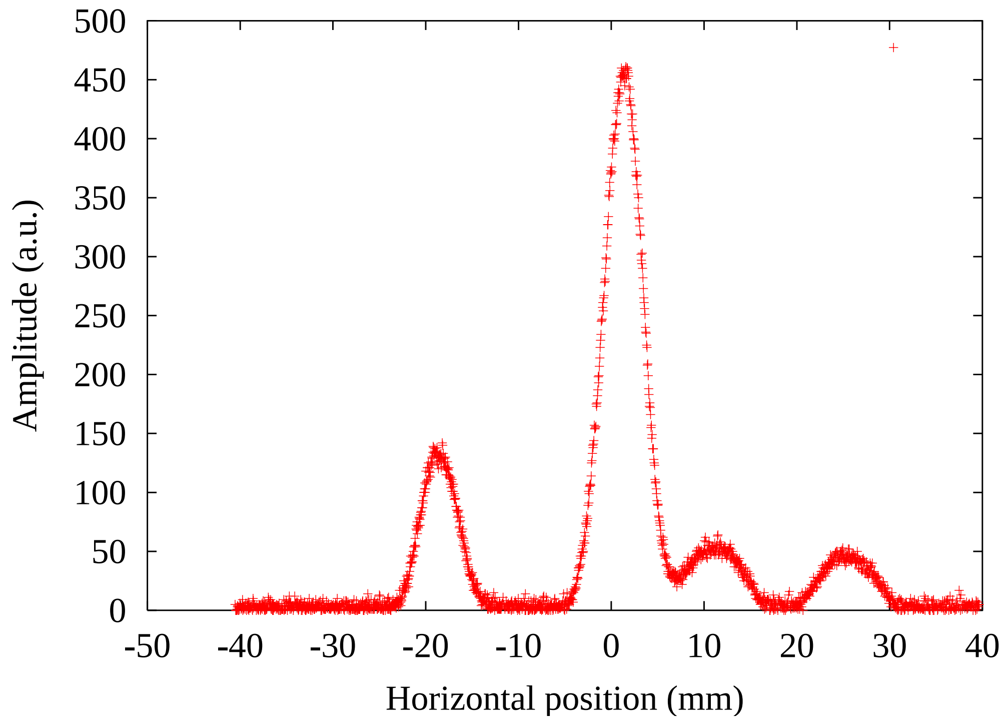

Figure 14: Horizontal beam profile measured by the flying wire scanner located in section 54 at the end of the capture process.

onto the horizontal axis of the five beamlets after separation: at the location of the flying wire in section 54, the islands' phase is such that two beamlets are projected onto the central core, thus explaining the rather large difference in amplitude between the central and the lateral peaks. Finally, it is worth noting that the left-right asymmetry in the profile measured by the flying wire, clearly visible in Fig. 14, is unphysical as it originates from the presence of one single photomultiplier located on one side of the vacuum chamber. This effect was cured by installing a second photomultiplier, so that the observed signal is obtained by summing the signals from two detectors one on each side of the vacuum pipe.

3.2.3 Extraction of a low-intensity beam

A new issue was considered during the 2003 tests, i.e. multi-turn extraction of the five beamlets. For this purpose, the elements used for the CT extraction were used. In this scheme a slow bump around the electrostatic septum is pulsed to push the beam towards the wires of the electrostatic septum. Then, two kickers installed in sections 21 and 9 create the so-called staircase, a closed bump five-turn long whose amplitude can be varied on a turn-by- turn basis. In the standard CT extraction, the beam is sliced onto the wires of the electrostatic septum, and the extracted beam undergoes an orbit distortion due to the deflection from the electrostatic septum in addition to the fast bump from section 21 to section 9. Around the magnetic septum in section 16 a slow bump generates the necessary orbit distortion for the beam to jump the septum blade. An example of the three bumps used for the CT extraction is shown in Fig. 15.

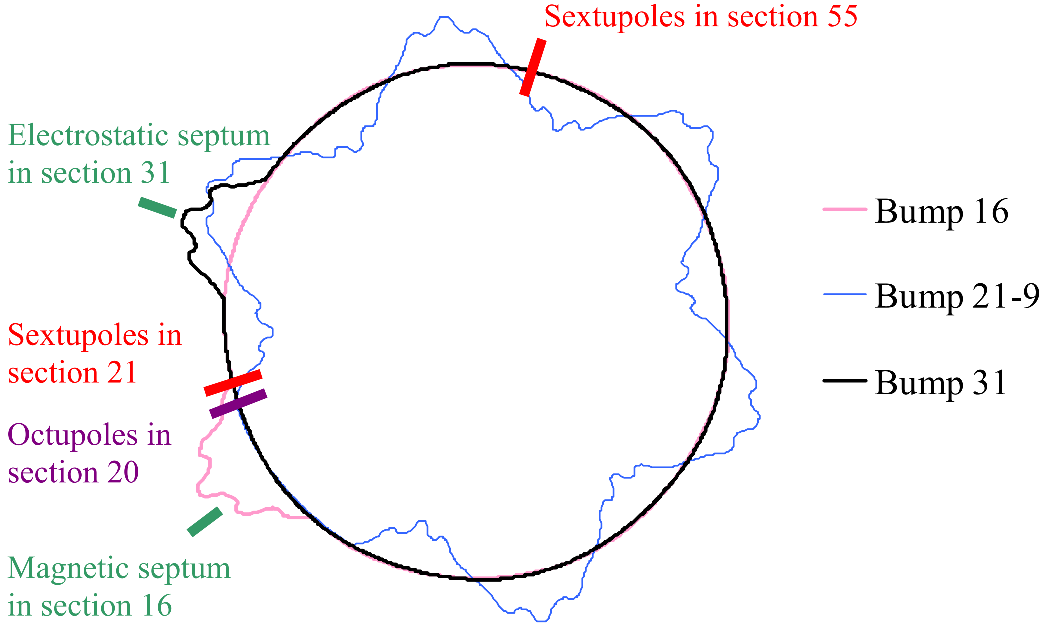

Figure 15: View of the two slow bumps (around the electrostatic septum in section 31 and the magnetic one in section 16) and the fast bump between sections 21 and 9.

The scheme used for the CT was also applied for the multi-turn extraction of the beamlets generated by adiabatic capture inside stable islands. Of course, in this case, the electrostatic septum is not used to slice the beam, but simply to increase the separation between the circulating beam and the one that should go through the magnetic septum in section 16.

Preliminary simulations [23] of the performance of the CT extraction under these new conditions showed that possible limitations are the strength of the kickers generating the five-turn bump and the presence of sextupoles in the region of the fast bump.

Both limitations were indeed experienced in the tests. The first one was the main source of extraction inefficiency, while the latter was so severe to prevent extraction at all. In fact, with the chosen sign of the sextupoles and the off-axis traversal, a strong inwards deflection was generated, almost compensating the effect of the bumps and the deflection imparted by the electrostatic septum. A solution for this problem came from the analysis of the symmetries of the process under study. In fact, the detuning with amplitude depends on K_3^2 and K_4 at the lowest perturbative order, where K_3 stands for the sextupolar gradient and K_4 for the octupolar one [24]. Therefore, changing the sign of K_3 does not affect the detuning very much, hence the phase space topology and the trapping, but would reverse the deflection due to off-axis traversal of the sextupole, from an inwards kick to an outwards one. Unfortunately, this has an impact on the linear chromaticity, which depends on K_3: the constraints imposed by the small number of degrees-of-freedom available to tune the PS machine did not allow to find a reasonable working point, i.e. tunes and chromaticities, for this new experimental condition.

An alternative solution was found by reversing the sign of K_4, i.e. changing the sign of the current feeding the octupoles. By doing this, a trade-off between the condition on the islands' phase at the location of the electrostatic septum and a reasonable islands' surface could be found. In Fig. 16 the horizontal phase space portraits are shown for the special setting used for extraction setting, i.e. with the octupoles in section 20 powered to -690 A and the sextupoles in section 21 powered to 350 A. Of

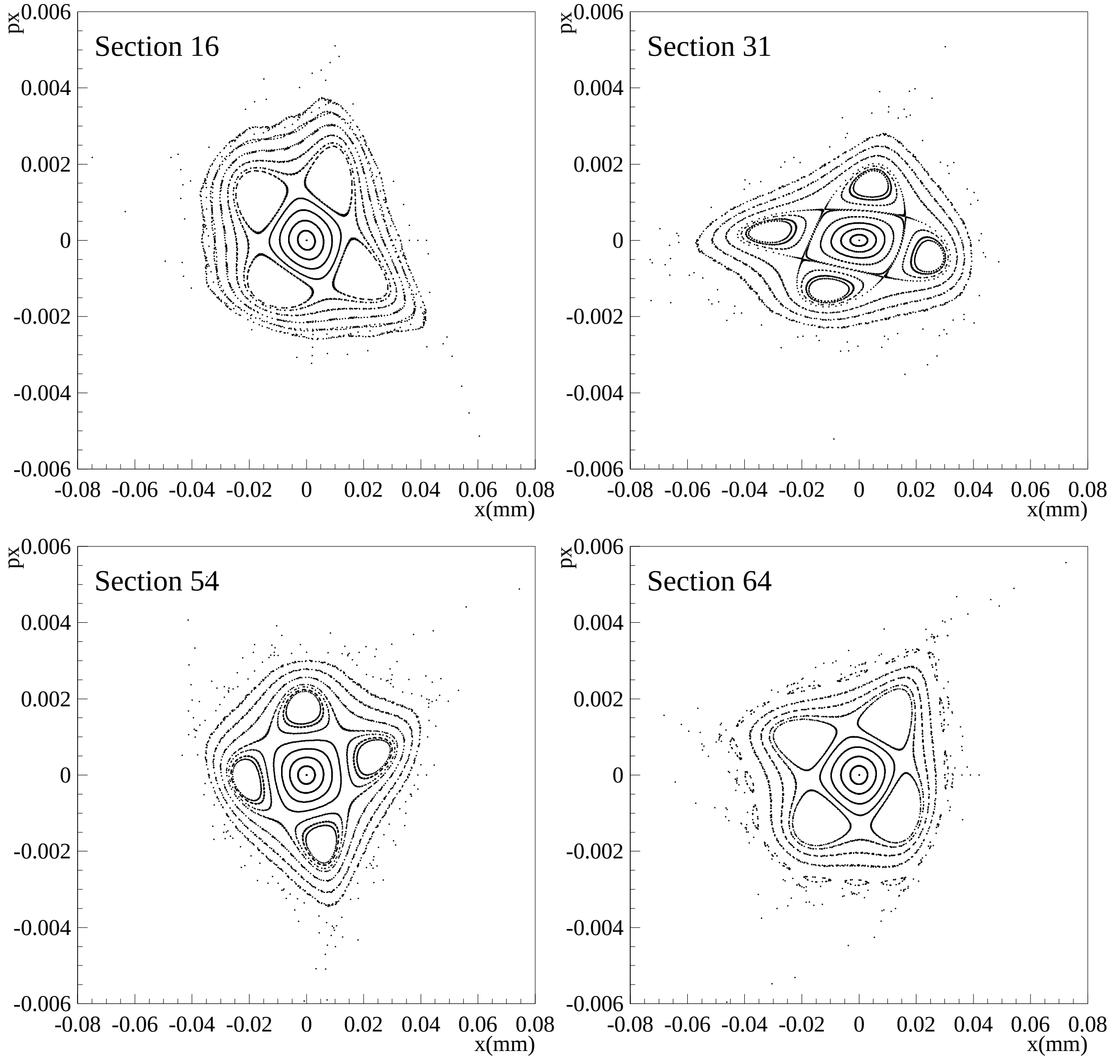

Figure 16: Horizontal phase space portrait in physical coordinates for the special conditions used in the extraction tests in 2003. The initial conditions of the form $(A, 0, 0, 0)$ have been tracked for 500 turns. The octupoles are located in section 20 (powered at -690 A) and the sextupoles are in section 21 (powered at 350 A). The tunes are $Q_H = 6.245$ and $Q_V = 6.30$. Different sections of the PS rings are presented here: section 16 (magnetic septum), section 31 (electrostatic septum), section 54 (horizontal flying wire scanner), section 64 (horizontal flying wire scanner).

course, under these special conditions, the sign of the detuning is change, thus imposing to cross the fourth-order resonance from above. In Fig. 17 a transverse beam profile in the horizontal plane at the end of the capture process is shown for the special configuration used for the extraction tests. No losses occur during the capture process. However, it is clearly visible that the amount of beam trapped inside the stable islands is much less that in the standard configuration.

The extraction tests were performed using the standard elements of the CT extraction. Due to a limitation in the fast bumpers, the extraction kicker is used to generate the required additional kicker strength. The main results are reported in Figs. 18 and 19.

In Fig. 18 the analog signals as measured by the wide-band pick-ups installed in the TT2 transfer line are shown. The five peaks refer to the five extracted beamlets. Although the same kick amplitude of the fast bump 21-9 should be used for the first four extracted beamlets, in practice, the non-closure of the extraction bumps make it necessary to introduce slight changes to the kick amplitude for the first four turns. The intensity of the fifth beamlet, namely the beam core, is higher than the first four ex-

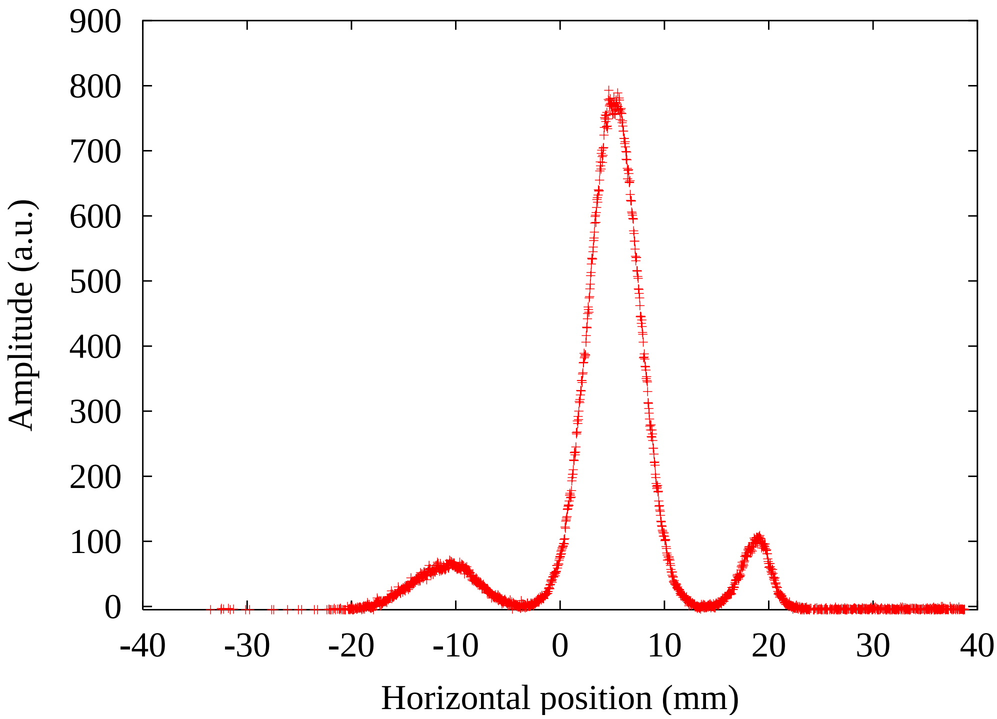

Figure 17: Horizontal beam profile measured by the flying wire scanner located in section 64 at the end of the capture process with the special conditions used for the extraction tests, namely octupoles located in section 20 (powered at -690 A) and sextupoles in section 21 (powered at 350 A).

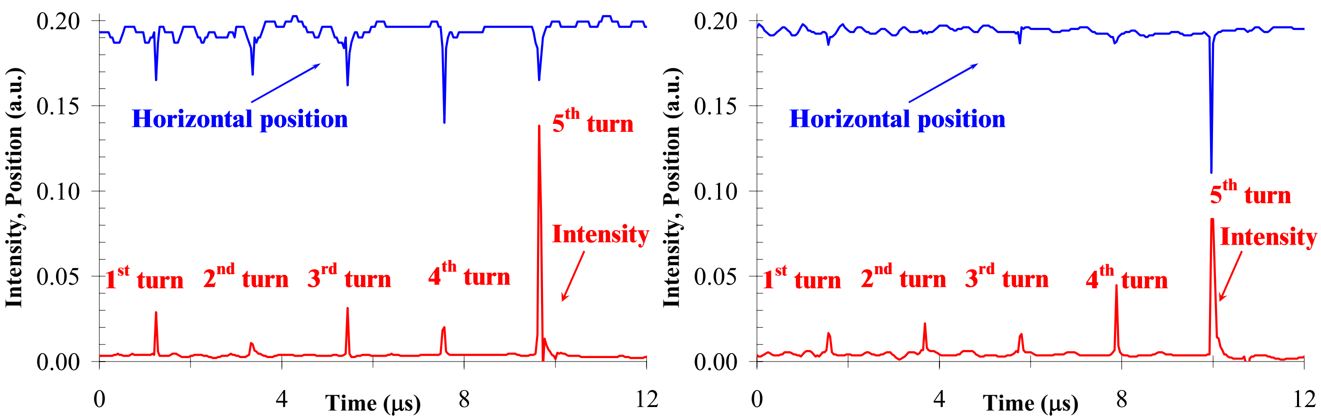

Figure 18: Analog signals from the two wide-band pick-ups installed in the TT2 line in section 208 (left) and 228 (right). The intensity of the last peak, representing the fifth-turn, or the central beamlet, is much higher than the others due to the small size of the stable islands.

tracted ones. This is a consequence of the small islands' surface, which makes it impossible to capture a reasonable amount of beam. By comparing the horizontal signals for the two pick-ups one clearly sees that the trajectories of the five beamlets differ, in particular the trajectory of the fifth differs considerably from those of the preceding beamlets.

This observation is also confirmed by the measurements performed in the horizontal plane with the Secondary Emission Monitors (SEM-wires) installed in the TT2 transfer line and normally used for emittance measurement of the extracted beam from the PS. The second Gaussian profile shown in the first monitor represents one of the beamlets featuring a different trajectory. All the horizontal profiles

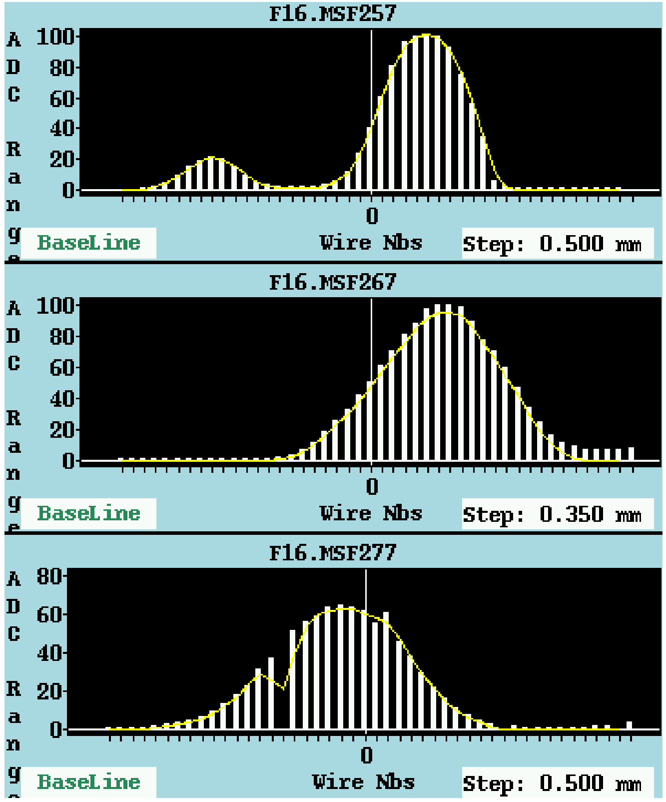

Figure 19: Horizontal beam profiles as measured by the Secondary Emission Monitors (SEM-wires) installed in the TT2 transfer line. The second Gaussian profile measured by the first monitor represents one of the extracted beamlets performing a different trajectory.

are Gaussian and no signs of heavy tails can be detected. In the vertical plane (not shown here), the profiles are Gaussian, too.

No attempt was made to optimise the extraction in the sense of reducing beam losses and improving trajectories by decreasing the differences between the beamlets. This choice was the natural consequence of the observed incompatibility, imposed by the available hardware, between optimal conditions for the capture and extraction. In fact, sextupoles in section 55 are required for generating the correct islands' phase at the electrostatic septum, but at the same time the induced trajectory jump prevents beam extraction. This, together with the constraints imposed by the working point control, is the main source of incompatibility between the two processes.

3.2.4 Capture with a high-intensity beam

Most of the MD time in the year 2003 was devoted to studying the capture process with a high- intensity bunch, in view of simulating the final version, i.e. after intensity upgrade, of the proton beam for the CNGS. According to preliminary computations quoted in Ref. [7] the space charge tuneshift should be of the order of few 10^{-3}. Therefore, it represents about one-third of the tune sweep through the resonance and it might be a serious obstacle for the proposed extraction mode. Therefore, capture tests with high-intensity bunch were the most important milestone for the year 2003.

The preparation started at the level of the PS-Booster machine, to setup a new single-bunch high-intensity beam (see Table 1 for a list of beam parameters). A careful adjustment of the PS machine was necessary to have a clean injection and to remove losses at the critical beam manipulations, such as beginning of acceleration and transition crossing. When proper conditions were achieved, the capture studies were resumed. Five beamlets were successfully established, not only at the nominal intensity for the upgrade scenario, i.e. 6×10^{12} protons per bunch, but even at higher intensity, the final record being 6.25×10^{12} protons. The experimental conditions, namely sextupoles and octupoles current, quadrupoles current, beam intensity, during the capture process for the record intensity are shown in Fig. 20. Contrary to the case with a low-intensity beam, losses were observed at the end of the capture

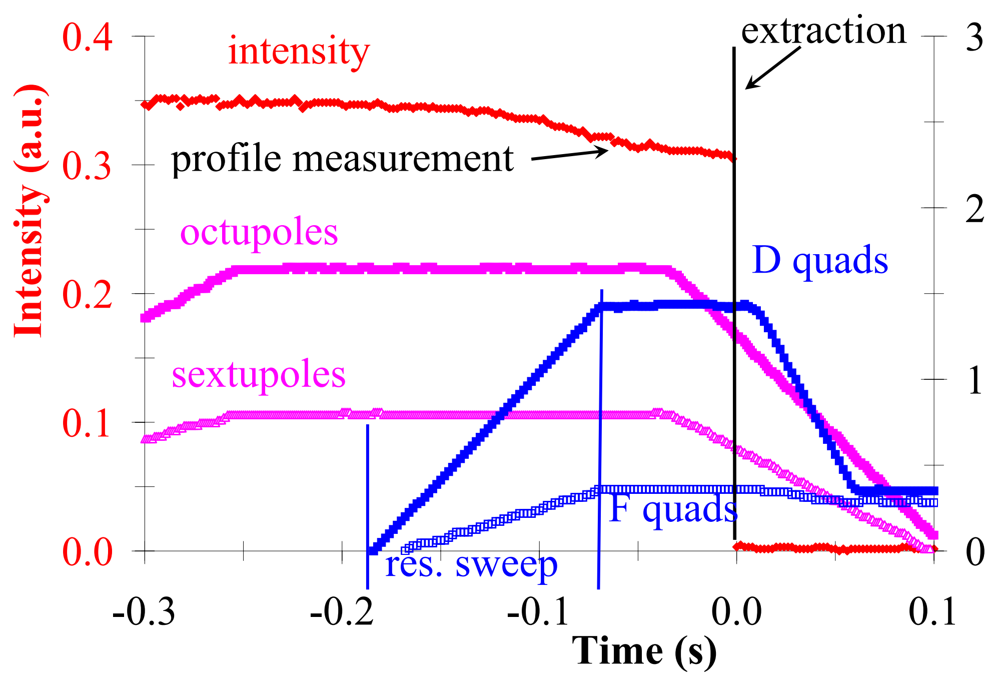

Figure 20: Experimental conditions during the tests for adiabatic capture inside stable islands with a high-intensity bunch.

process, during the separation stage. In spite of the efforts made to optimise the tunes and the speed of resonance-sweep, no major improvement was achieved. Possible explanations for such losses will be discussed in the next sections. Finally, in Fig. 21 the typical transverse beam profiles after the capture process are shown.

After having shown the possibility of trapping particles inside stable islands even for a high-intensity bunch, the issue of capture efficiency, i.e. the number of particles in the beamlets with respect to those in the core, was considered. Tests were performed by shaking the beam just prior to resonance crossing and measuring the result beam profile at the end of the capture. The beam is excited by means of the q-metre kicker used both in automatic mode and in manual mode, i.e. with the possibility of varying the kick amplitude. This device allows also varying the timing of the first kick as well as the number of kicks imparted to the beam. In Fig. 22 the profiles with and without beam perturbation are shown. The increase in trapping efficiency is clearly visible. The data analysis is still in progress and it will be presented in Ref. [25]. It is worthwhile mentioning that if this method is to be used to modify the beam distribution in view of improving the capture efficiency, the direction of resonance crossing does matter as space charge breaks the symmetry between crossing the resonance from below or above. In fact, from the point of view of single-particle dynamics the detuning with amplitude could be changed, by acting on the sextupole and octupole, so to have a perfect symmetry between the two directions of crossing. However, in presence of space charge-induced tune spread different phenomena occur according to whether core or tail particles cross the resonance first. In the first case, the so-called core emittance blow-up is generated, useful for acting on the capture efficiency, while in the latter no measurable emittance blow-up, and hence improvement in the capture efficiency, is obtained (see also Ref. [26] for a detailed account on recent studies on this topics).

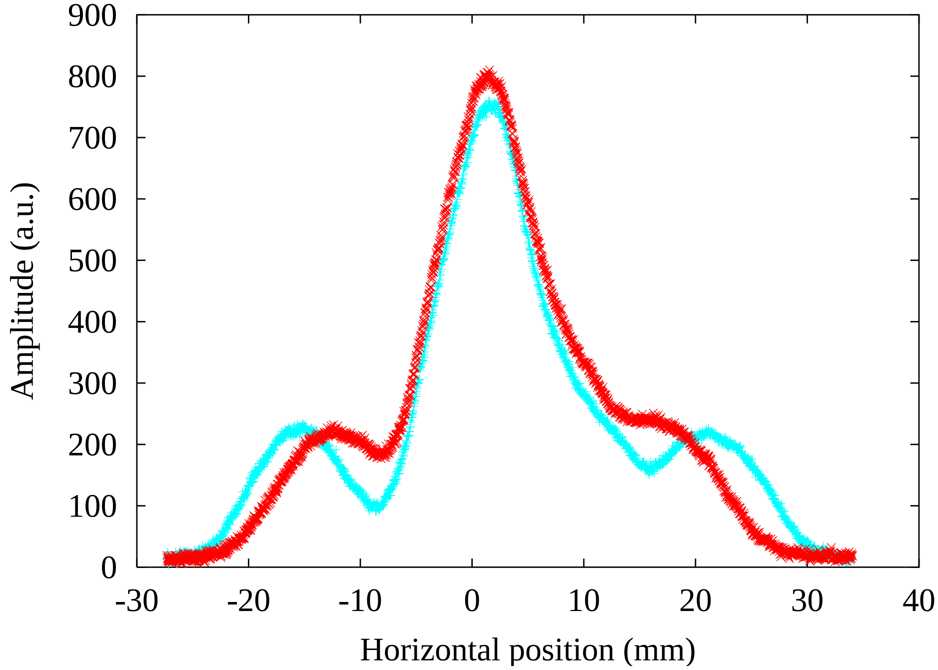

Figure 21: Horizontal beam profiles as measured by the PS wire scanner in section 54, for the nominal intensity (6×10^{12} p/b, magenta) and the record intensity (6.25×10^{12}, red). In the case of record intensity, the beamlets separation was reduced to decrease beam losses during the capture process.

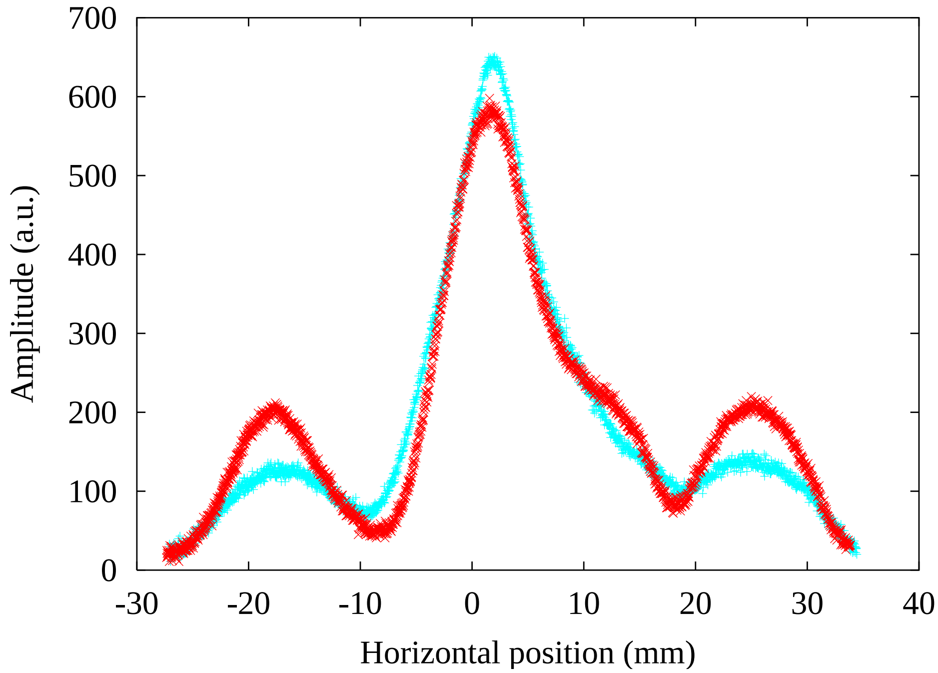

Figure 22: Horizontal beam profiles as measured by the PS wire scanner in section 54, for the nominal intensity (6×10^{12} p/b) without any beam perturbation (magenta) and with beam perturbation (red).

4 Route towards a multi-turn extraction

Although most of the fundamental questions concerning the use of adiabatic trapping as a technique for beam extraction over few turns were tackled and encouraging results were obtained, a number of points still need detailed investigations. These points concern both beam physics as well as hardware issues.

4.1 Numerical simulations

Most of the numerical simulations reported in previous papers (see Refs. [7, 8, 11, 14, 15]) referred to simple models of horizontal betatronic motion, including nonlinear effects due to sextupoles and octupoles. Of course, the results should be cross-checked against simulations for realistic models of the PS machine. In particular, it will be important not only to simulate the capture process but also the multi-turn extraction including all the details such as the influence of the fast bump, with the unavoidable fast tune variation, on the extraction performance.

Considerable efforts were devoted in measuring dynamical quantities, e.g. tune vs. amplitude and momentum offset, useful to fit an accurate model of the beam dynamics [22]. However, limitations in the physics implemented in the MAD-8 program [27], namely, the treatment of the dynamics of off-momentum particles, made it necessary to setup a crash program to convert the model to the syntax of the MAD-X code [28]. Even in this case, limitations related with the large bending radius and the need of tracking with thick elements, impose the use of PTC [29] available within MAD-X. The PTC implementation is still under development and additional tests are necessary before numerical simulations can actually start.

4.2 Beam instrumentation

Three systems are crucial for the tests of the new multi-turn extraction: the multi-turn measurement system, the flying wire, and the screen in the magnetic septum. The first performs phase space reconstruction, allowing probing the phase space topology, the second measures beam profiles, thus enabling monitoring the various stages of the capture, while the third one allows tuning the extraction process. The performance of the first two instruments is satisfactory and they are expected to be kept in good working conditions. As far as the screen in the septum is concerned, attempts were made to use it during the extraction tests in 2003, but not meaningful information was extracted. It would be extremely helpful if maintenance work could be made during the forthcoming shutdown to have the screen operational in 2004.

In case the proposed multi-turn extraction will replace the present CT, it is highly probable that additional flying wires will be required in the region of the extraction septum.

4.3 Capture

The most critical point is the presence of beam losses during the capture process whenever a high-intensity bunch is considered. The losses are not present when the low-intensity bunch is used. The main difference between the two cases is the value of the vertical emittance (see Table 1). Furthermore, it is important to remind that the standard PS octupoles used for the capture tests, have a reduced horizontal aperture. This imposes tight constraints, as these elements cannot be installed everywhere in the PS ring, but only in a straight section with a special vacuum pipe. This can only occur in even straight sections where the horizontal beta-function has a minimum. This is the reason why the set of two octupoles is located in section 20. However, this has two main inconveniences: firstly, the magnetic strength has to be increased due to the small horizontal beta-function to obtain the necessary effect on beam dynamics [30]; secondly, the ratio between the vertical and the horizontal beta-function is about 2, thus meaning that a strong perturbation of the vertical dynamics is generated by the octupole. This hypothesis can be tested with numerical simulations and also with measurements next year, provided that a solution to move the octupoles from section 20 to another section with maximum horizontal beta-function is found. A complete discussion of the solutions found can be found in Ref. [31], here it will be mentioned that it is foreseen to install an SPS octupole in section 21 during the shutdown 2003/2004.

In Fig. 23 the horizontal phase space portraits for the proposed solution with octupoles and sextupoles both installed in section 21 are shown. In addition to the advantages already mentioned, this

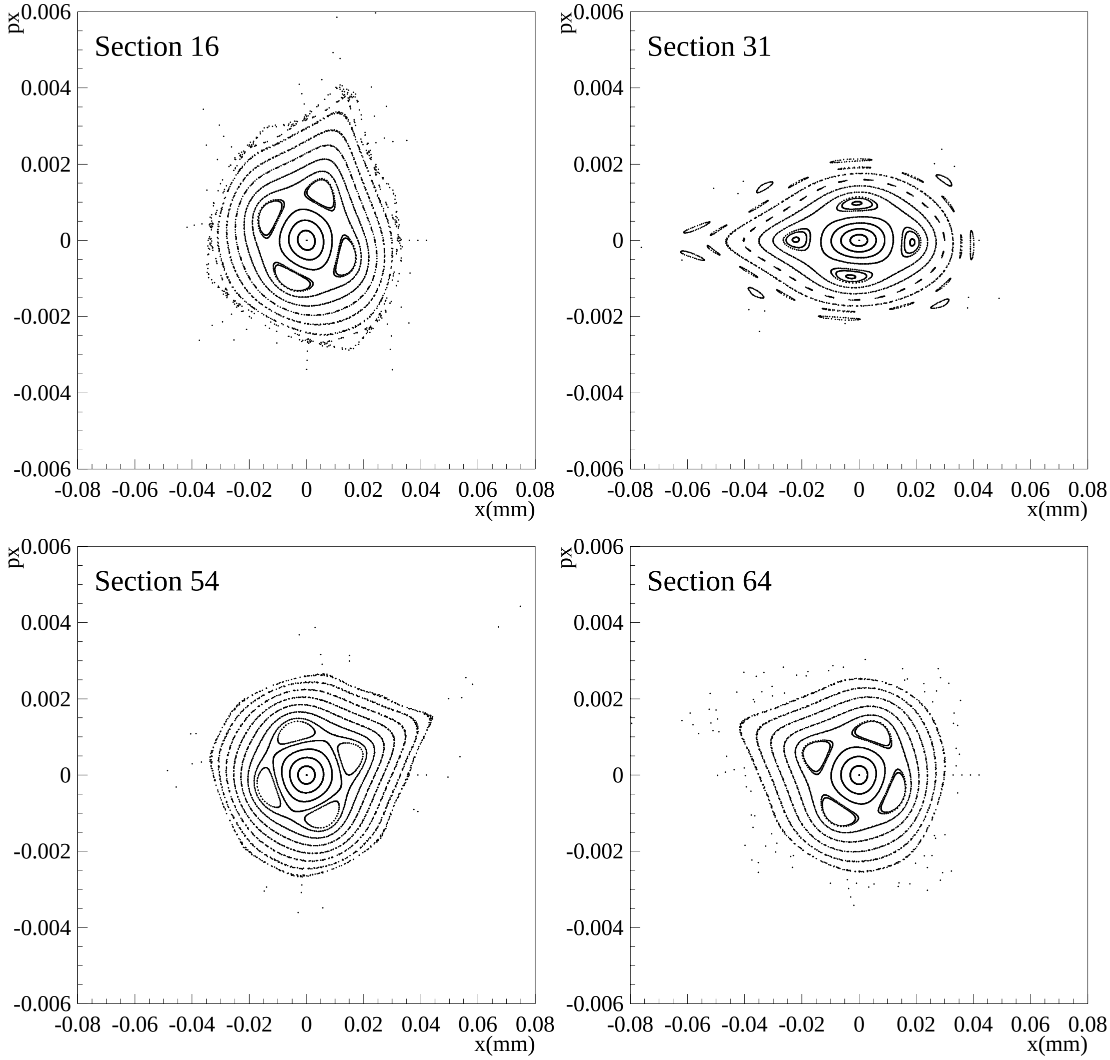

Figure 23: Horizontal phase space portrait in physical coordinates for the proposed configuration for the tests in 2004. The initial conditions of the form $(A, 0, 0, 0)$ have been tracked for 500 turns. The octupoles are located in section 21 (powered at 350 A) and the sextupoles are in section 21 (powered at 350 A). The tunes are $Q_H = 6.255$ and $Q_V = 6.30$. Different sections of the PS rings are presented here: section 16 (magnetic septum), section 31 (electrostatic septum), section 54 (horizontal flying wire scanner), section 64 (horizontal flying wire scanner).

configuration features also a correct islands' phase at the location of the electrostatic septum, meaning that the incompatibility between capture and extraction observed during the tests performed in 2003 might be removed.

4.3.1 Sextupole and octupole magnets

On the long-term, new sextupoles and octupoles should be built. In the case of sextupoles the standard PS elements presently installed fulfill the requirements for the tests of the new multi-turn extraction. However, two magnets are required to achieve the necessary strength and they occupy about 0.7 m in a straight section. A new sextupole could allow reducing the occupancy as well as having enough strength to leave open the possibility of a multi-turn extraction at 26 GeV/c.

In the case of the octupoles, the present elements are limited both in terms of mechanical aperture (horizontal plane) as well as in strength. Again a single element with the appropriate aperture might alleviate the problems of space occupancy while allowing reaching 26 GeV/c. Rough specifications (see Table 2) have been produced to ease estimating the cost and the manpower needed for construction.

Comments	Sextupole	Octupole
Aperture type	circular	circular
Chamber size H× V (mm× mm)	150×75	150×75
Diametre inscribed circle (mm)	145	145
Overall length (mm)	500	500
Approximate transverse dimensions (mm)	600	600
Max current (A)	700	700
Max ramp time (for I_{max}) (ms)	50	50
Inductance (mH)	10	10
Resistance (mΩ)	60	60
Integrated strength[a] (for $I \leq 100$ A)	$18\ \mathrm{T\,m^{-1}}$	$900\ \mathrm{T\,m^{-2}}$
Limit of magnetic linearity (A)	500	500
Region of good field (mm)	± 50	± 50
Cooling	demineralised water	demineralised water
Flow (for $\Delta P \approx 10$ bars)	3 l/min	3 l/min

Table 2: Main parameters for the new sextupoles and octupoles for the multi-turn extraction.

[a]The integrated strength is given by $\int \frac{d^2 B_y}{dx^2}\, d\,l$ for the sextupole and by $\int \frac{d^3 B_y}{dx^3}\, d\,l$ for the octupole.

4.3.2 Power converters

The sextupole and octupole magnets needed for the new multi-turn extraction are fed by two standard PS power converters (Tekelec type) recuperated from the Robinson wigglers no more in operation since the shutdown of the LEP collider and more than twenty-year old.

These power converters use a thyristor-bridge and a transistor bank in series. The transistor bank is composed of hundreds of transistors connected in parallel. This technical solution, although quite common in the seventies, is now a source of concern due to aging of electronic components. On the long-term it is foreseen to replace all these power converters due to the maintenance costs being too high. A summary of the power converters performance with the existing magnets (sextupoles and octupoles) is presented in Table 3.

4.4 Extraction

To minimise the costs of the tests for the new multi-turn extraction, most of the hardware was recuperated. This was the case for the magnets, the power supplies, and, of course, also for the extraction elements. In fact, the devices for the CT extraction have been used. This is certainly the most efficient approach at the stage of preliminary tests. However, it might not be the best solution in case such a new approach replaces the present technique.

A detailed study of the performance of the present CT extraction scheme applied to the new multi-turn extraction is planned. In parallel, the analysis of an alternative scheme is also under consideration. Such an alternative scheme should overcome some of the drawbacks of the CT extraction layout, namely the overall complexity of the layout (made of two septa, two slow bumps, and one fast bump), a bump covering a large fraction of the machine circumference, as well as limitations in the strength of the present fast bumpers.

Comments	Sextupole	Octupole
Magnet		
Inductance (mH)	1.5	30
Resistance (mΩ)	30	57
Max current (A)	700	400
Number of magnet in series	2	1
Dynamic		
dI/dt max (kA/s)	7	15
max rise time (ms)	100	100
round of time (ms)	$10-20$	$10-20$
Operation		
Current	unipolar	unipolar
Control system	PS standard	PS standard
Tekelec power converter		
type	T7	T7
Max current (A)	700	700
RMS current (A)	450	450
Max voltage (V)	650	650
Min current (A)	10	10
Zero current	blocking	blocking
Voltage Bipolar	yes	yes
Current Bipolar	yes with thyristor switch	yes with thyristor switch
Max voltage needed		
$R\,I_{\max}$ (V)	42	22.8
$L\,dI/dt$ (V)	21	450
$V_{\max}$ (V)	63	472.8
Remarks	One choke of 5 mH is placed in series with the magnet	with 15 kA/s, the rise time will be around 30 ms

Table 3: Main parameters of the power converters presently in operation for the multi-turn extraction tests.

As the electrostatic septum is no longer necessary for the new multi-turn extraction, as the beam is no more sliced, the solution under study simplifies the scheme by removing the electrostatic septum and the related slow and fast bumps. Then, a different fast bump is created around the magnetic septum in section 16 in addition to the existing slow one. Preliminary computations show that fast bumpers could be installed in sections 12 and 20 and the required deflection angle would be about 2 mrad. A detailed study will be performed in the coming months. Here, rough estimates of the hardware based on the quoted figures will be presented.

After the removal of the presently installed magnetic elements the available length (in both straight sections) is limited to 948 mm because of the remaining vacuum sector valves. To reduce the demands on the fast bumper pulse generators the magnets need to be installed in vacuum tanks, thus minimizing the vertical aperture. The magnet aperture is chosen such that a metallised ceramic chamber of rectangular cross-section (for the reduction of the longitudinal impedance) can be accommodated. For the fast bumper magnets the basic parameters required are presented in Table 4. Given these parameters a provisional proposition, relying as much as possible on existing, but recent, demonstrated technology, is shown in Fig. 24. This implies use of large diameter thyratrons with about 10 kA fast current

Parameter	Value
Deflection angle θ (mrad)	2
Magnetic rigidity $B\,\rho$ at 14 GeV/c (T m)	46.7
Integrated field (T m)	0.094
Kick duration (five turns) (μs)	11
Available space (m)	0.948
Magnet aperture (H) (m)	0.128
Magnet aperture (V) (m)	0.08
Effective magnetic length (m)	0.808

Table 4: Basic input design parameters for the new fast bumper system.

switching and carrying capability, and SF_6-filled cable Pulse Forming Networks (PFNs), identical to those installed for the PS-Booster kickers [32]. Further in-depth study and prototyping is required for a definitive proposal.

It can be seen that a common power supply for each step in both straight sections is used. This, of

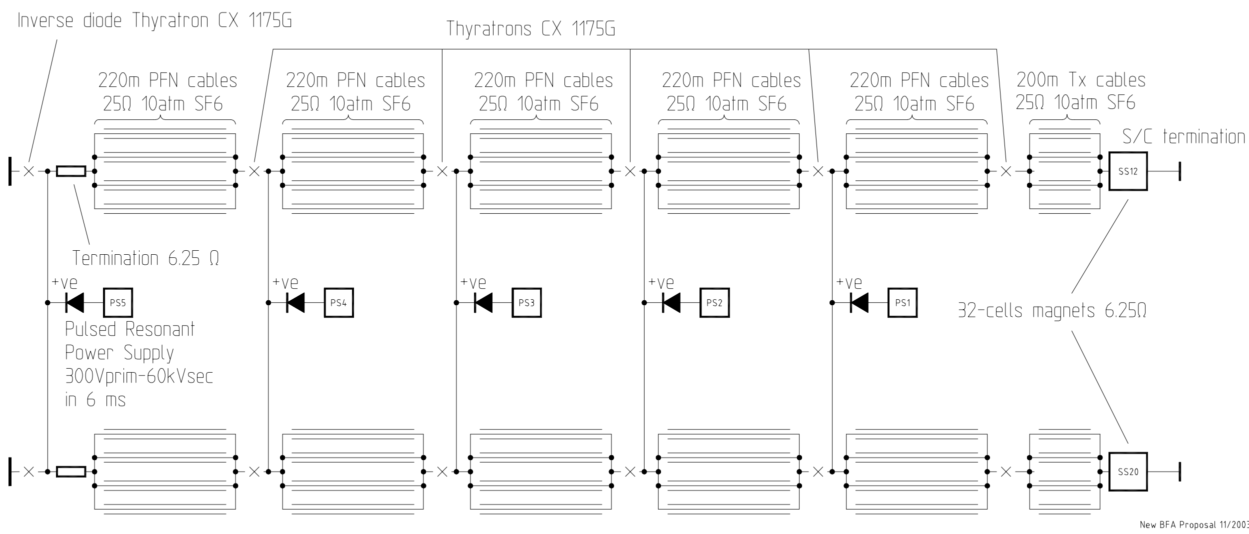

Figure 24: Proposed layout of the new fast bumper.

course, does not allow adjusting the kick differentially. It should also be noted that the kick value of the following step should not be lower than the preceding step, although there is some operational margin. As at this stage of the study it is not certain that the deflection power of approximately 0.1672 T m, corresponding to ≈ 3.56 mrad, of the PS extraction kicker will be sufficient for the fifth bunch, a five step fast bump is proposed.

In case the kick rise-time of one long magnet is considered not acceptable, two shorter magnets having together the same deflection power as a single magnet but providing an improved rise-time can be envisaged. The price ticket of the vacuum tank including the magnets will not change noticeably, however, the cost for the pulse generator (and thus the major part of the total bumper project) will practically double. An evaluation of the system performance, based on simple scaling laws, is reported in Table 5. It is evident, as mentioned earlier, that an in-depth study and some development work and prototyping have to be made before a final system can be proposed.

Parameter	One magnet/ straight section	Two magnets/ straight section
Effective magnetic length (m)	0.808	0.804
System impedance Z_0 (Ω)	6.25	6.25
Magnet current (kA)	7.406	7.443
Nominal charging voltage (kV)	47.68	47.92
Maximum charging voltage (kV)	60	60
Maximum deflection angle at 14 GeV/*c* (mrad)	2.517	2.50
Estimated rise-time (10 to 90) % (ns)	485	290
Estimated rise-time (5 to 95) % (ns)	560	340
Estimated rise-time (2.5 to 97.5) % (ns)	610	365

Table 5: Estimated pulse generator and magnet performance parameters.

4.5 Working point control

One of the peculiarities of the PS machine is that its working point, namely Q_H, Q_V, Q'_H and Q'_V, are set by means of three coils installed in the gap of the main magnet, namely the so-called pole-face-windings (PFWs) and the figure-of-eight loop (F8L). The PFWs are installed in each magnet half-unit, while the F8L is common to the two half-units of the same magnet. Therefore, only three degrees of freedom are available to tune the machine, instead of the four normally needed. The present control mode will be called three-current in the following. This implies that, in the best case, the desired working point can be obtained only by a complex tuning procedure, and, in the worst case, such a working point cannot be obtained at all.

Since their design [33, 34], the PFWs can be separated into two coils, called Narrow and Wide after the width of their conductors. A sketch of the electric connection is given in Fig. 25 (left). At the origin, the separation of each PFW into Narrow and Wide coils was foreseen to allow controlling the working point by means of five independent parameters. However, this option was never implemented.

Limiting effects for the performance of the PS machine have been pushed further continuously since its construction. An improved working point control capability would certainly be extremely useful for routine operation. In the case of the proposed multi-turn extraction, the possibility of precisely controlling the working point is of paramount importance. For these reasons, the analysis of possible solutions to remove present limitations has been undertaken in the framework of the activities of the Study Group for the new multi-turn extraction in the PS machine. The idea consists in implementing the five-current control of the PWFs and F8L by separating the Narrow and Wide coils of the PWFs and installing additional power converters. In this mode, five power converters are used to feed PFWDN, PFWDW, PFWFN, PFWFW and F8L (see Fig. 25 (right) for a sketch of the proposed electric connections).

From the hardware point of view, everything had been done to use these two different modes. Five power converters are installed as well as a special patch-panel with electromechanical switches to change the feeding modes. Less than one hour is necessary to change from three-current to five-current mode and vice-versa.

Preliminary tests were performed during the last PS MD session held on November 11$^{\text{th}}$ 2003. The change of configuration between the three- and five-current made was successful, but it was impossible to control correctly the current of the PFWDN, PFWDW, PFWFN, and PFWFW. This was traced back to an electromagnetic coupling. In fact, the PFWs are placed inside the PS magnet gap. Therefore, these windings are magnetically coupled with the dipole. When the PS Main Power Supply (MPS) is ramping, a voltage is produced in the PFW windings, very much like a transformer where the primary winding is the main dipole and the secondary windings are the PFWs. The PFW power supply regulation keeps control of the current. However, the perturbation is so strong and fast that an unwanted

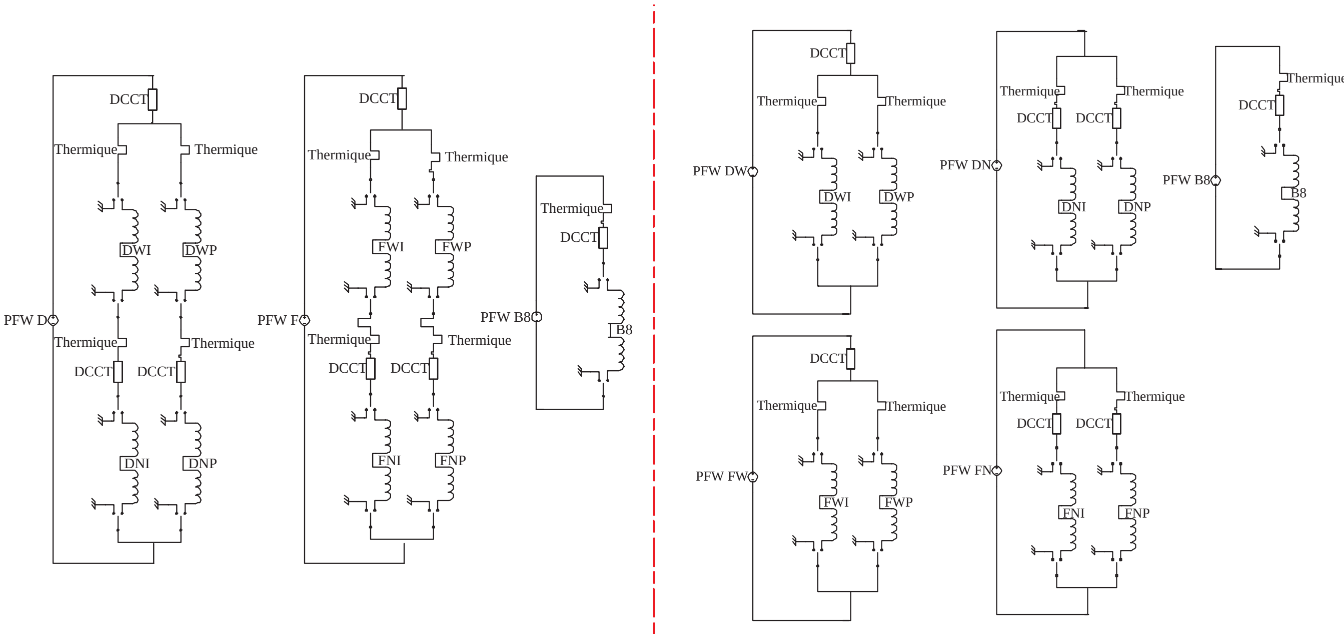

Figure 25: Sketch of the connection of the PFWs (Narrow and Wide coils) for the present three-current configuration (left) and the proposed five-current configuration (right).

current is induced in the PFWs. In normal operation, such an induced current is measured and the PFW current reference included a correction to obtain the right value of the current. This is achieved at the level of the application program used to tune the working point of the PS machine. In the five-current mode, the coupling between the PFW and the dipole magnet is bigger, meaning that the induced voltage is bigger (the corresponding induced currents are a factor of four larger).

Following the analysis made, it is proposed to change the regulation system in such a way that the perturbation generated by the MPS is taken into account within the control loops of the PFW power converters (see Fig. 26 for a sketch of the proposed system). Of course, an in-depth study will be required to assess the functionality of the new device. Thus, the Narrow and Wide coils of the PFW are expected to be controllable independently. This new control loop may be applied both to the three- as well as to the five-current mode, thus allowing tests of the five-current mode during MD sessions in 2004, while keeping the three-current mode for normal operation. If the five-current mode proves to work satisfactorily with the new control loops, it is proposed to have the new system operational for the 2006 startup.

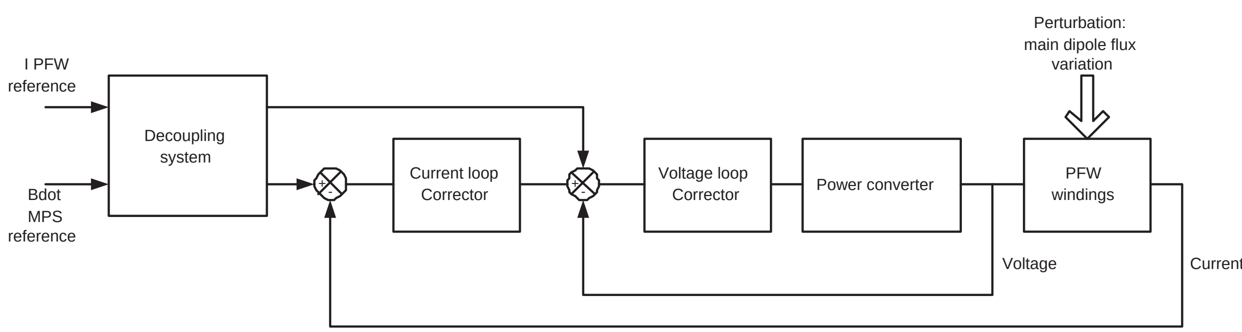

Figure 26: Principle of the decoupling system. The PFW current reference and the MPS reference will be used to control the PFW power converter. The system will act on the PFW current and voltage references

5 Resources

5.1 Capture

5.1.1 Sextupole and octupole magnets

- Sextupole: it is assumed that two complete magnets will be built, one to be installed in the ring and another as a spare. The manufacturing cost is estimated to be about 50 kCHF. As far as the resources are concerned, one person is required for the magnetic design and the preparation of the technical specification (15 kCHF), and a draftsman to prepare the specification drawings (10 kCHF). Hence, the overall costs can be estimated around 75 kCHF. One year (four months for preparatory work before placing the contract and eight months for the manufacture itself) is the expected delay for delivery at CERN of the two sextupoles starting from the approval of the activities.
- Octupole: as the octupole is very similar to the sextupole magnet, the similar arguments holds also in this case and similar costs, manpower, and delay estimates apply.

5.1.2 Power converters

The replacement of these power converters is already taken into account in the PS consolidation project. Hence no budget request is made for this item, but the AB/PO Group expects to be supported to replace these very old equipments as part of the consolidation project. However, on the short-term, these power converters will be kept for powering the two magnets and no work has to be planned. The maintenance and operation works will be assured by the AB/PO Group and no additional manpower is requested for this.

5.2 Extraction

The resources needed for the hardware study and construction in view of the new extraction layout, are estimated at two man-years, as detailed in Table 6 where the Personnel + Material (P+M) estimate is given. It is worth mentioning that no resources are allocated yet to this topic in the AB/BT staff plan. At the present stage of the study the cost estimate given in Table 7 can be advanced for a new fast bump

Item	Quantity
Engineer	0.5
Electronics technician	0.75
Electro-mechanic	0.5
Draftsman	0.25
Hardware cost	100

Table 6: Estimate of required P+M effort (in man-years and kCHF) to prepare a detailed design study, including some prototyping.

system. It has to be noted that at present no installation site is free for use. A possible installation site could have been the location of the present fast bumper installation in building 359. However, as an overlap in testing of a new installation and the exploitation of the present one is necessary, this option is not valid. It could be envisaged to use the first bay of building 367, actually occupied by the former PS e^+/e^- injection kickers and some test installations. It is not yet clear whether that would liberate sufficient space. It is however quite clear that there is not enough space for the solution with a faster rise-time. A new building and cable annex should then be found or constructed in the vicinity (less than

Item	Quantity	Unit price × quantity (kCHF)
Vacuum tanks	2	340
Magnets, connections etc.	2	320
PFN and Tx cables + accessories	12	1400
Thyratron switch tanks	12	1000
Pulsed resonant power supplies	5	220
Oil, SF_6 services	1	220
Electronics + controls	12	500
Total		4000

Table 7: Cost estimate of principal bumper items.

200 m) of the straight sections concerned, i.e. 12 and 20, with enough access to the PS ring to install the transmission cables. Obviously, the cost of that and the dismantling of existing equipment must be added to the above cost estimates.

The estimate of the manpower, not included in the AB/BT staff plan, required to produce and install the one magnet per straight section solution is given in Table 8. From this it is evident that the study

Item	Quantity
Engineer	3
Designer draftsman	2
Mechanics	3
Electro-mechanic	2
Electronics technician	4
Mechanics technician	1

Table 8: Manpower estimate for production and installation of the single magnet solution (in man-years).

and prototyping phase, followed by a project proposal and eventual acceptance will take a considerable time. The construction, installation and commissioning will hardly be less than three years, given all required resources are available. It is therefore essential that the present CT equipment, namely kickers and septum, is kept in good working order for well beyond the start-up of the CNGS. The minimum reasonable consolidation effort (P+M) to be invested during the long shutdown 2005/2006 into these systems has been estimated:

- Kicker requirements for continued use of present CT: the estimate for the consolidation of the present fast bumper equipment is given in Table 9. The manpower required by the kicker section (3.5 man-years) is already included in the AB/BT staff plan.
- Septum requirements for continued use of present CT: running with CNGS type beam and using the old continuous transfer ejection scheme in the PS will lead to additional losses, hence an increase in the radiation dose for the electrostatic septum is to be expected. Since the limits of the present oil insulated high-voltage feed-throughs are unknown, and the damage of polluting the PS vacuum in case of failure are very high, it seems prudent to replace the feed-throughs with 3M Fluorinert^{TM} insulated feed-throughs. This system needs permanent regeneration of the insulating liquid, but in case of failure the damage done to the PS vacuum is far less. Also, the oil change of the present feed-throughs every 12 weeks of operation will be unnecessary with the

Item	Quantity	Unit price × quantity (kCHF)
New staircase generator (NSG9/21)	1	60
Reserve staircase generator (DFA243)	1	60
Pedestal generators (PED9/21)	3	75
DFA242	1	25
Fine timing	1	25
Total		245
Engineer	0.5	
Electronics technician	2.5	
Electro-mechanic	0.5	

Table 9: Estimate of material costs and manpower (in man-years) for the consolidation of the CT kickers.

new system, hence the radiation dose taken by the personnel will be much less (presently up to 1 mSv per oil change). The new feed-through and regeneration system has still to be developed. This work, consuming 0.65 man-years, is already included in the present AB/BT staff plan. The detailed required effort (M+P) is shown in Table 10.

Item	Quantity	Unit price × quantity (kCHF)
SEH31 feed-throughs	3	40
Regeneration station with tubing	1	20
Control electronics	1	10
Total		70
Engineer	0.1	
Electronics technician	0.3	
Electro-mechanic	0.25	

Table 10: Estimate of material costs and manpower (in man-years) for the consolidation of the electrostatic PS septum.

5.3 Working point control

The study and implementation on the existing equipments will require about 0.5 man-years of one technical engineer and 0.1 man-years of one engineer both in 2004. As far as the budget is concerned, the hardware modifications, electronic card, cables, etc. will cost around 10 kCHF. The PFW power converters are more than twenty-five years old and cause a lot of breakdowns, the critical components being the electronics cards, the electronic devices, the connectors. For this reason the replacement of these devices is already included in the PS consolidation program for an amount of 600 kCHF. In case of positive results of the five- current mode tests, the AB/PO Group will replace all these power converters by renovated or new ones.

It is worthwhile stressing that the modifications at the level of the power converters to allow a five-current mode is certainly a necessary but not sufficient condition for improving the flexibility of tuning the working point of the PS machine. Another important item is the program to control the power converters, linking the hardware parameters (currents) with the beam parameters (tunes and chromaticities). Failure of having an operational program will vanish all the efforts made to improve the hardware.

Therefore, enough resources should be allocated to write such a program in parallel with the studies on the power converters. No estimate of these resources is attempted here.

6 Possible implementation

Following the discussion of the results achieved so far, and of the remaining issues, including resources, possible scenarios for the implementation of the proposed solution are listed here:

- 2004: The crucial point is the presence of losses during the capture with the high-intensity beam. In the previous sections, it is suggested that the location of the octupoles could account for these losses. Presently, a request has been made to install an SPS octupole in the section 21 to allow further tests to be performed during the run 2004. It is important to gather all the possible measurements to allow further analysis during the long shutdown 2004/2005. This hardware modification is also important as it might remove the incompatibility between capture and extraction for high-intensity bunch. Therefore, even more realistic tests than those performed in 2003 could be envisaged in 2004.
  In parallel, on the side of numerical simulations, activities will continue to analyse the data collected so far, and to deepen the understanding of the various processes required for the new multi-turn extraction.
  In case of positive outcome of the different activities, hardware specification and construction/prototyping could be launched at the end of 2004, beginning of 2005.
- 2005: During the long shutdown the only activity at the hardware level would be the developments concerning the five-current working point control, and, if necessary, the construction of the new sextupoles and octupoles. Therefore, the efforts will mainly focus on simulation campaign and follow-up of the hardware studies.
- 2006: The commissioning of the CNGS beam should be made with the nominal scheme, i.e. a single batch beam delivered to the SPS after slicing by means of the standard CT at nominal intensity, i.e. 3.3×10^{13} per PS batch. In parallel, MD activities could continue with the available hardware, possibly improved at the level of the magnets and power converters and working point control.
  As it will be unlikely to have the new fast bumper system available for the tests, no guarantee for a reasonable extraction efficiency is given. However, in case of positive results, preliminary tests of delivering the beam to the SPS using the new scheme could be attempted.
- 2008: According to the estimates presented in previous sections, the new fast bumper system might be available for the startup 2008, provided specifications were available by the end of 2004 beginning of 2005 and the prototypes confirm the correctness of the assumptions made. Therefore, commissioning of the new multi-turn extraction could take place, including the adiabatic capture, and the extraction proper using the new, simplified layout.

7 Summary and outlook

In this report the activities and the results achieved in the years 2002/2003 concerning the proposed multi-turn extraction at the PS have been presented and discussed in detail.

Following the encouraging results of the numerical simulations performed on simple models, an intense campaign of MDs was launched. The main results can be summarised as follows: the adiabatic capture was successfully tested at low-intensity, without any beam loss. At high-intensity, beam trapping and beamlets separation was achieved. Tests for studying how to increase the fraction of beam trapped in the islands were successfully performed and the data analysis is in progress. However, under these conditions, losses were observed and they could not be removed so far. Extraction of the five generated beamlets was tested using the low-intensity bunch: a beam extracted over five turns was observed in the TT2 transfer line, even though the efficiency was rather low and difference in trajectory between the five beamlets was observed. Hardware constraints made capture of high-intensity bunch and extraction mutually exclusive.

The analysis of the pending issues, beam physics and hardware, have been presented too, including also estimates of the resources needed to define and possibly specify a project. The conclusions of the analysis are summarised in Table 11.

	Items	Material (kCHF)		Personnel (Industrial support) (man-year)		Personnel (CERN staff) (man-year)	
		Avail.	Not avail.	Avail.	Not avail.	Avail.	Not avail.
Project definition	Kickers		100				2
Project completion	Octupoles		50		0.17	0.17[a]	
	Sextupoles		50		0.17	0.17[a]	
	Power converters	–	–	–	–	–	–
	Kickers		4000[b]		3		12
	Working point control	610				0.6	
	Total	610	4200		3.34	0.94	14
		P+M (kCHF)					
	Grand total	751	6801				

Table 11: Summary of the conclusions concerning the resources needed to have the proposed multi-turn extraction replacing the present CT at 14 GeV/c. In the conversion, one man-year has been considered equivalent to 150 kCHF.

[a] depending on the time of the request for magnets construction, availability status might change.

[b] the price is for the solution based on a single magnet/straight section. Additional costs in case of need for a new building are not taken into account.

The various items discussed in this report have been grouped according to whether the costs/resources are needed for the preparation of the final design report or for the construction stage. The kickers for the new layout of the multi-turn extraction require prototyping and additional detailed study: following the conclusions of these activities, the cost estimate for construction might need revision.

An evaluation of the maintenance costs of the key hardware for the present CT extraction have been performed too, giving a total of 70 CHF and 0.65 man-year for the electrostatic septum and 245 CHF and 3.5 man-year for the fast bumpers: unfortunately, such an amount cannot be saved by implementing the proposed extraction scheme due to the delay for the study and construction of the new fast bumpers for the extraction in section 16. Finally, a possible scenario for the implementation of the proposed solutions has been discussed.

For the sake of completeness, it is worth mentioning that two points have not been addressed in this report, namely the implications of delivering a bunched beam, on harmonic 8 or 16, to the SPS, and of increasing the extraction energy to 26 GeV/c. These two issues need clarifications, mainly in terms of MD studies at the SPS. Although these studies were already included in the 2003 MD schedule, radiation issues imposed to cancel these studies. In light of these events it would be important to resume these activities next year with a rather high priority to achieve a final statement on the SPS capabilities/needs.

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