A NOVEL TECHNIQUE FOR MULTI-TURN INJECTION IN A CIRCULAR ACCELERATOR USING STABLE ISLANDS IN TRANSVERSE PHASE SPACE

M. Giovannozzi, J. Morel, CERN, Geneva, Switzerland

Abstract

By applying a time-reversal to the multi-turn extraction recently proposed, a novel approach to perform multi-turn injection is described. It is based on the use of stable islands of the horizontal phase space generated by means of sextupoles and octupoles. A particle beam can be injected into stable islands of phase space, and then a slow tune variation allows merging the beam trapped inside the islands. The results of numerical simulations will be presented and discussed in details, showing how to use the proposed approach to generate hollow bunches.

INTRODUCTION

Charged particles injection into a circular accelerator can be performed by three distinct approaches: single-turn, multi-turn, and charge-exchange injection [1]. The first method is based on the use of a septum magnet to deflect the injected beam towards the central orbit of the receiving machine and a fast deflector, a so-called kicker, to adjust the angle of the incoming beam so to match both position and angle of the central orbit. While the septum magnet can be pulsed or not, the kicker provides a deflection over one machine circumference only, which will be the length of the injected pulse. The second method aims at injecting more than one turn. This is normally obtained by means of a septum magnet, kicker and an appropriate slow bump used to paint the phase space so to generate the appropriate transverse and/or longitudinal beam distribution. Finally, the charge exchange method [2] is a refined version of the multi-turn injection where H^- ions are injected and stripped at the injection point: this has the advantage of generating high-brightness beams.

In recent years, a novel method to perform multi-turn extraction from a circular particle accelerator was proposed [3-6]. It is based on particle trapping inside stable islands of transverse phase space generated by nonlinear magnetic field, such as sextupolar or octupolar. This method proved to work well not only in numerical simulations [3-6], but also in a series of experiments carried out at the CERN Proton Synchrotron (PS) machine [7-9].

The time-reversal property of the dynamics involved in the novel extraction process allows generalizing the approach to multi-turn injection. Indeed, the idea consists in injecting the beam into stable islands of phase space and then to vary the tune so to merge back the beamlets into one single beam [10]. This requires a closed orbit bump generated by kickers so that one of the islands is used to inject the beam. Then, once all the islands are filled, the bump is collapsed and the tune is varied to change the beam distribution towards the final shape. The number of injected turns depends on the resonance used for generating the stable islands. In the next section the results of numerical simulations performed on a simple model are presented to support the validity of the proposed concept.

NUMERICAL SIMULATIONS

The model

The model used to study the proposed injection technique consists in a simple FODO cell with a sextupole and an octupole located at the same longitudinal position, both represented in the single-kick approximation [11]. For the application under study, only the horizontal plane is relevant. Therefore, the evolution of the beam dynamics can be obtained by using a 2D one-turn transfer map, which turns out to be a polynomial map of the form:

$$\begin{pmatrix} x_{n+1} \\ x'_{n+1} \end{pmatrix} = R(\omega_n) \begin{pmatrix} x_n \\ x'_n + x_n^2 + \kappa x_n^3 \end{pmatrix}, \qquad (1)$$

where the co-ordinates (x, x') are adimensional normalised co-ordinates [11], $R(\omega)$ represents a rotation matrix of an angle $\omega = 2\pi\nu$ and κ depends on the ratio between the strength of the sextupole and the octupole with a weight given by the value of the optical beta-function at the location of the nonlinear magnetic elements [6], namely

$$\kappa = \frac{2}{3} \frac{K_3}{K_2^2} \frac{1}{\beta_x} \qquad \lambda = \frac{1}{2} K_2 \, \beta_x^{3/2}, \qquad (2)$$

and

$$(X, \quad X') = \lambda (x, \quad x') \qquad (3)$$

where $(X, \quad X')$, $(x, \quad x')$ stand for normalised Courant-Snyder co-ordinates and adimensional normalised co-ordinates, respectively. The angle ω is indeed a function of the turn number: for the results presented in this paper the time-dependence of ω is always chosen linear and in all the plots, as well as in the numerical and analytical computations reported here, the special adimensional normalised co-ordinates are used.

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Results of simulations

The numerical simulations focused on two resonances, namely the fourth- and the third-order resonance. In the first case, the injection occurs over four turns. The value of the coefficient κ is kept constant throughout the process and equal to -1.5. The initial beam distribution is chosen to be Gaussian in both horizontal position and angle with a sigma of 0.02 in both dimensions. The number of initial conditions is 10^6. The tune is swept from $\nu = \mathbf{0.245}$ to $\nu = \mathbf{0.255}$ in 2×10^4 turns. The results concerning the evolution of the beam distribution are shown in Fig.1.

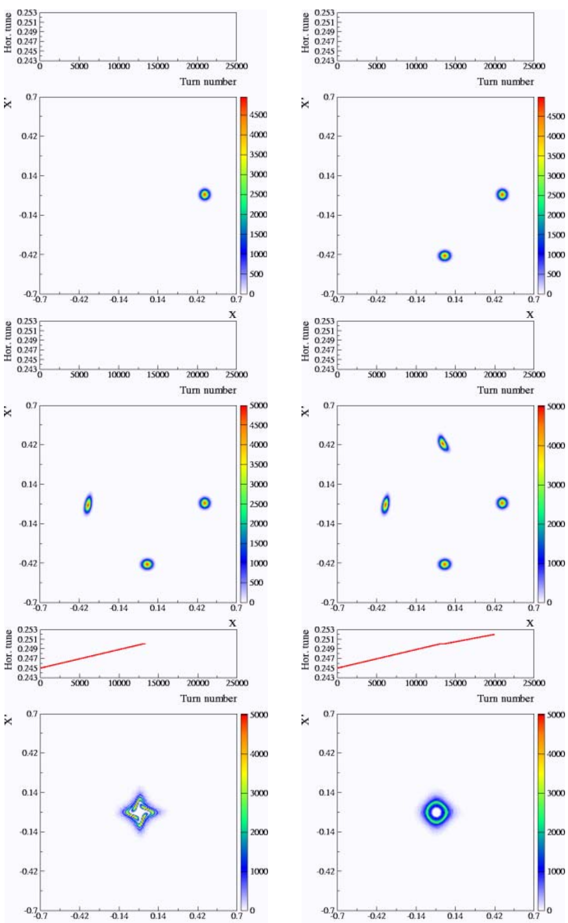

Figure 1: Multi-turn injection by means of trapping in stable islands of transverse phase space. Four turns are injected and the beamlets merged by crossing the fourth-order resonance. The tune variation is reported in the upper part of each plot. As a result a hollow beam in the transverse phase space is generated.

The beam is injected using the outermost island lying along the positive horizontal axis, which is supposed to be located beyond the injection septum blade. At the end of the first four turn, the injection process proper is over: the beam ellipse is distorted due to the effect of the nonlinear effects. The next stage consists in changing the tune so to sweep through the resonance and then to merge the four beamlets into one single structure. The final stage of the beam evolution is rather striking: the beam distribution is not at all a standard Gaussian, but it is a hollow distribution, with the beam spread over an annulus in phase space.

Such an effect is very likely due to the fact that the islands' size is also changing during the whole process, being a function of the linear tune [12]. In particular, their size tends to zero while approaching the exact resonance condition. This means that whenever the tune is sufficiently near to the resonant value, the islands become so small that almost no beam can be transported towards the origin.

The projected beam distribution along the horizontal phase space axis is shown in Fig. 2, where the initial (left part) as well as the final distribution (right part) is shown.

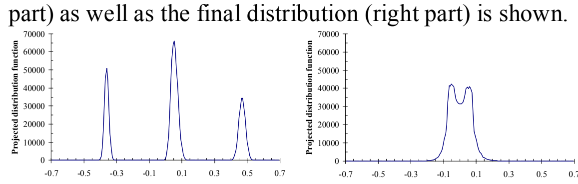

Figure 2: Initial (left) and final (right) distribution function for the four-turn injection. The two islands centred at the origin with opposite angles are projected onto the central peak visible in the initial distribution function.

The three peaks visible in the left part are indeed the result of the projection of the four injected turns shown in Fig. 1 (centre right part). Therefore, the single central peak is indeed the superposition of two injected turns. The different width at the three distributions is an effect of the distortion of the beam ellipse induced by the nonlinear effects. The hollow beam distribution shown in the right part of Fig. 2 reflects the observation made that the final beam is not at all Gaussian.

A possible solution to this issue is rather straightforward, in the sense that, as the fourth-order resonance is stable, a fifth turn could be injected at the origin of phase space. In practice this implies that the origin of phase space is displaced by the closed bump created by kickers beyond the septum blade. Once the first turn is injected, the bump amplitude is reduced so that the stable island is beyond the septum blade: in this condition the injection process can continue for additional four turns. The properties of the first injected turn. i.e. number of particles and sigma, can be used to tailor the shape of the final beam distribution, e.g. to fill the hole in the centre.

On the other hand, this peculiar feature of the final beam distribution might even turn out to be a big advantage in some conditions, such as when dealing with high-intensity beams. In fact, it is well-known that the largest space charge tune shift affects particles in the beam core. This explains why efforts are devoted to reducing the beam density around the origin of phase space, in particular by developing techniques to generate flat- or hollow-bunches in the longitudinal phase space [13-15]. Therefore, one could use the proposed approach to shape the beam distribution so to reduce the space charge effects at injection, where they are particularly harmful.

It important to stress that the simulations presented here do not take into account the Coulomb interaction between the particles, hence the observation made should be confirmed by more detailed simulations taking into account also space charge effects. On the other hand, one could argue that, due to the peculiar beam distribution, space charge effects should be highly reduced, hence the final beam distribution might be preserved even under the influence of Coulomb interaction.

Finally, it is worthwhile stressing that during the whole injection process no particle's loss is observed.

Numerical simulations performed for the third-order resonance confirmed the results presented in this paper that is the proposed method allows injecting three turn without losses and the final beam distribution is a hollow one. However, unlike the four-turn injection, it is not possible to perform injection in the origin of the phase space, as the third-order resonance is unstable, and the beam would be lost in few turns.

CONCLUSIONS AND OUTLOOK

In this paper a novel method to perform multi-turn injection is presented. Such a technique is the time-reversal equivalent of the multi-turn extraction recently proposed and based on the use of stable islands of transverse phase space generated by nonlinear magnetic element such as sextupoles and octupoles.

The proposed approach proved to work well according to the results of numerical simulations performed on a simple model describing the horizontal betatronic motion in a FODO cell with sextupole and octupoles. No particle losses are observed both using a fourth- and third-order resonance. Furthermore, the method allows generating hollow distributions in the transverse phase space, which could be extremely interesting in the case of multi-turn injection of high-intensity, space charge-dominated beams.

The next step in this study will be the quantitative analysis of the main parameters of the final beam distribution to be compared with those of a classical multi-turn injection.

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