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NEW METHODS TO CREATE HOLLOW BUNCHES

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Abstract

New methods to create hollow distributions in longitudinal phase space based on manipulations with a double harmonic RF system at high energy are presented with application to the PS Booster synchrotron (PSB). Whereas the first tentative to create hollow bunches at the PSB aimed to improve the performance of the PSB itself, these new methods are expected to reduce the limitations due to direct space charge forces in the receiving PS (where no double harmonic RF system is available) after transfer. One method aims to introduce empty phase space in the centre of the phase space by recombination of the beam in one bucket with another empty bucket. The second method is based on redistribution of phase space surfaces during the transfer of the beam from one second harmonic sub-bucket to another. During that process, phase space surfaces are exchanged and low density from the periphery ends up in the centre, whereas the high density surfaces from the centre are transferred to the periphery. Both methods have been simulated by particle tracking. The second method has been applied in practice at the PSB. The set-up turned out to be simple and fast, and to yield hollow distributions with good reproducibility.

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Abstract. New methods to create hollow distributions in longitudinal phase space based on manipulations with a double harmonic RF system at high energy are presented with application to the PS Booster synchrotron (PSB). Whereas the first tentative to create hollow bunches at the PSB aimed to improve the performance of the PSB itself, these new methods are expected to reduce the limitations due to direct space charge forces in the receiving PS (where no double harmonic RF system is available) after transfer. One method aims to introduce empty phase space in the centre of the phase space by recombination of the beam in one bucket with another empty bucket. The second method is based on redistribution of phase space surfaces during the transfer of the beam from one second harmonic sub-bucket to another. During that process, phase space surfaces are exchanged and low density from the periphery ends up in the centre, whereas the high density surfaces from the centre are transferred to the periphery. Both methods have been simulated by particle tracking. The second method has been applied in practice at the PSB. The set-up turned out to be simple and fast, and to yield hollow distributions with good reproducibility.

INTRODUCTION

The performance of accelerators limited by transverse direct space charge forces, i.e. the "Laslett" tune shift, may be improved by reducing the peak current inside a bunch. For given bunch length and intensity, the peak current is decreased by creating "flat" bunches. One possibility to obtain flat bunches is to create hollow distributions in longitudinal phase space. The scheme used at the first attempts [1] at the PSB aimed to introduce empty phase space, before bunching, in the centre of the coasting beam. This was tested and brought close to operation recently [2].

In this paper, new methods to create hollow bunches in longitudinal phase space, based on RF gymnastics with a double harmonic RF system are presented. Those methods are in general not suitable to improve the performance of the machine in which they are applied. But they are intended to alleviate limitations due to space charge after transfer into a receiving machine without other means for bunch flattening.

PRINCIPLE

Both methods presented in this paper have been simulated by particle tracking in longitudinal phase space for a beam on a high energy flat-top (with increased length). Therefore, appropriate forms for the RF functions have been inserted into the equations of motion :

$$\frac{d}{dt}\Delta E = \frac{q}{T_0}\left[V_1(t)\sin\left(2\pi\frac{\tau}{T_0}-\phi_1(t)\right)+ V_2(t)\sin\left(4\pi\frac{\tau}{T_0}-(2\phi_1(t)+\phi_{21}(t))\right)\right]$$

$$\frac{d}{dt}\tau = \frac{\eta}{\beta^2\gamma E_r}\Delta E \quad ,$$

where τ denotes the time (negative τ for the "head" of the bunch) and ΔE the energy offset of an individual particle w.r.t. a reference. T_0, η q and E_r are the revolution time, the momentum slip factor, the charge and the rest mass of the particle. V_1 and V_2 are the voltages of the first and second harmonic RF system. The phase ϕ_{21} between the two RF system is a crucial parameter, whereas the phase ϕ_1 of the principal RF system is not directly accessible (influenced by RF loops), but plays only a minor role and included for completeness only.

Recombination with an Empty Bucket

The method presented in this section has been triggered by tomographic reconstruction of bunch splitting and is similar to schemes in [3]. The basic idea is to merge the beam in one bucket with an empty bucket by appropriate gymnastics with a double harmonic RF system. Adjusting the RF parameters in an appropriate manner, one may insert a lot of empty phase space in the centre leading to a low density there, and insert very little empty phase space in the periphery.

A simulation of the whole process by particle tracking is shown in Fig. 1. RF parameters shown in the upper image are inserted into the equations of motion and yield phase space portraits below. During the first 14 ms, starting from a first harmonic bucket (with only a very small or no voltage of the second harmonic system), a double bucket structure has to be created such that the second bucket is outside the area occupied by the beam. This is achieved by increasing the voltage V_2 of the second harmonic RF system and shifting the phase

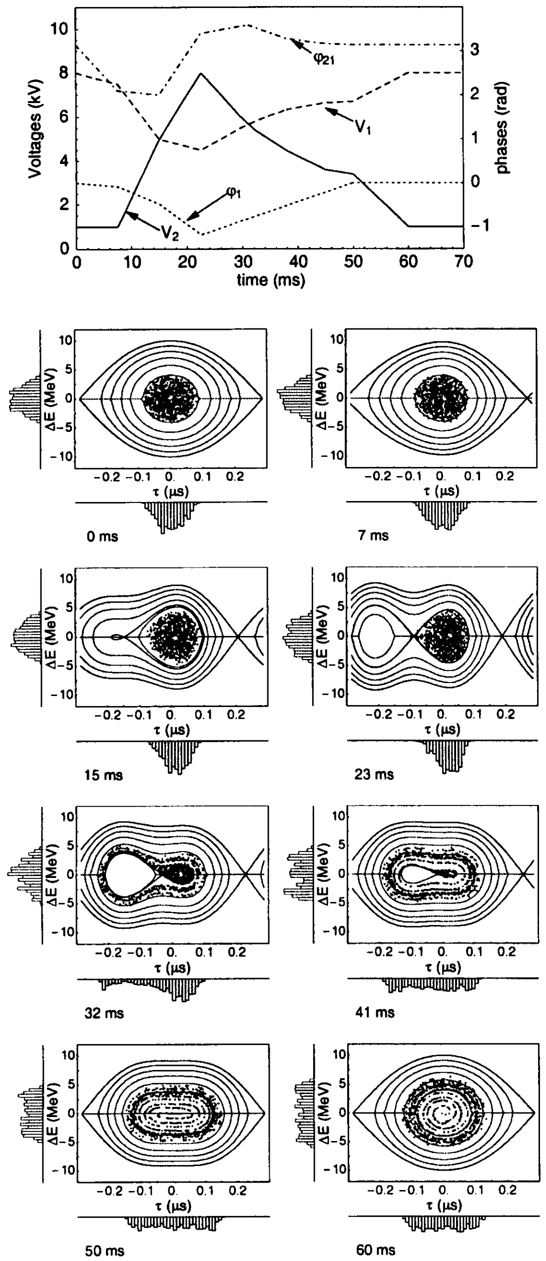

FIGURE 1. Creation of hollow bunches by recombination of the bunch with an empty bucket. RF parameters versus time (above) and phase space portraits.

ϕ_{21} to an appropriate value (sufficiently far from π). Then the empty bucket is increased to the desired size while keeping the full bucket just big enough to contain the beam. The situation after 23 ms is the starting point of the merging process. RF parameters are adjusted such that first mainly the full bucket collapses filling the periphery of the merged bunch and, towards the end more and more empty phase space is mixed in by collapsing the empty bucket. Care is taken that the buckets do not collapse too fast towards the end of the merging process, by changing the RF parameters slowly. At time 50 ms the merging is completed and during the last 10 ms, the RF system is brought back to the initial state.

Redistribution of surfaces in phase space

When applying asymmetric merging of a bunch with an empty bucket, one has to be careful to generate the double bucket structure such that the small bucket is outside the area occupied by the beam. For instance, if the emittance of the beam would be larger, the small bucket in Fig. 1 after 15 ms would not be empty. In the method outlined here, this situation is created on purpose (see situation after 10 ms in Fig. 2) and is the starting point of the redistribution process.

The process is best explained with the help of Fig. 2. Tracking with the RF functions shown in the upper image leads to phase space distributions plotted below. Particles have different shades (or colours if viewed with a device rendering colours) depending on their initial distance from the bunch centre in order to distinguish particles stemming from different initial locations. During the first 10 ms, a double-bucket structure is created with the small bucket inside the area occupied by the beam. Then, the RF parameters are adjusted such that the initially large bucket shrinks and releases phase space surfaces, which start to surround the two buckets. Simultaneously, the initially small bucket grows and captures phase space surfaces surrounding it. Thus, along the process, surfaces are transferred from one bucket to the other and high density surfaces from the centre are brought to the periphery. The total acceptance of the two second harmonic buckets together is slightly larger at the end of the process in order to mix some low density from the periphery with the dense core.

EXPERIMENTAL RESULTS

Redistribution of phase space surfaces necessitates relativeley simple RF gymnastics and does not lead to a significant blow-up of the total longitudinal emittance. This makes it particularly interesting for the PSB and, thus, this method has been tested experimentally. After a short set-up time, hollow bunches have been created with good reliability and reproducibility, even with the highest intensity possible in the PSB. Whereas the simulations had only been done for a long flat-top, the method has been tested experimentally on the high energy part of the ramp as well. The advantage is that the total cycle time is not increased and the process may take longer.

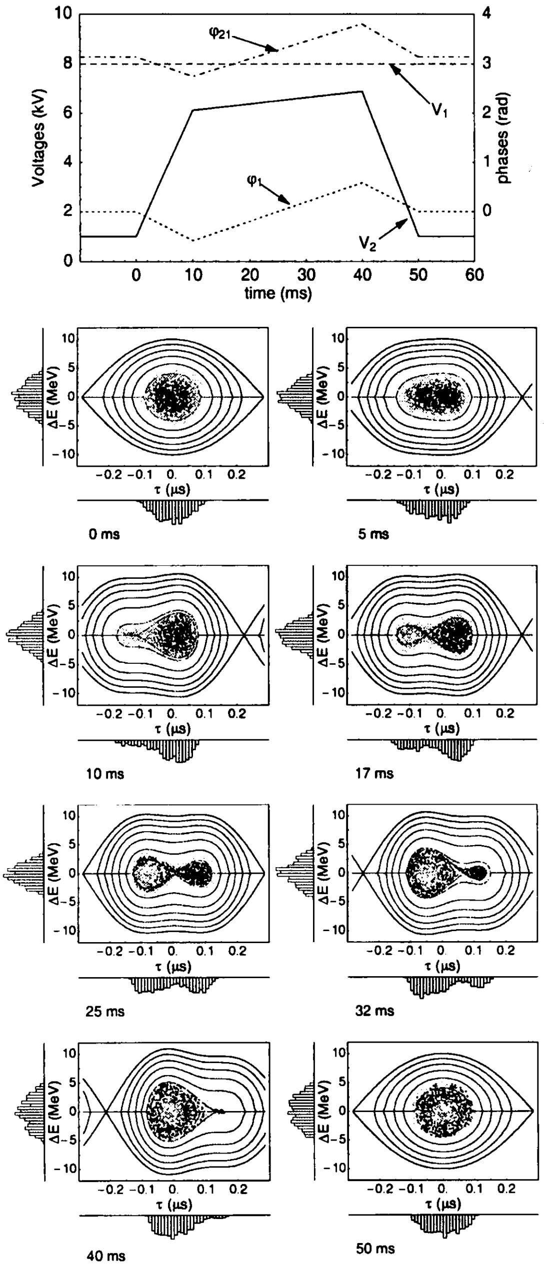

FIGURE 2. Creation of hollow bunches by redistribution of phase space surfaces. RF parameters versus time (above) and phase space portraits.

A tomographic reconstruction of the longitudinal phase space after creation of a hollow bunch is shown in Fig. 3. On top, the profile with hollow bunch (solid line) is compared with the profile of a normal bunch without redistribution (dashed line). The peak current is clearly reduced, with a negligible increase of the bunch length.

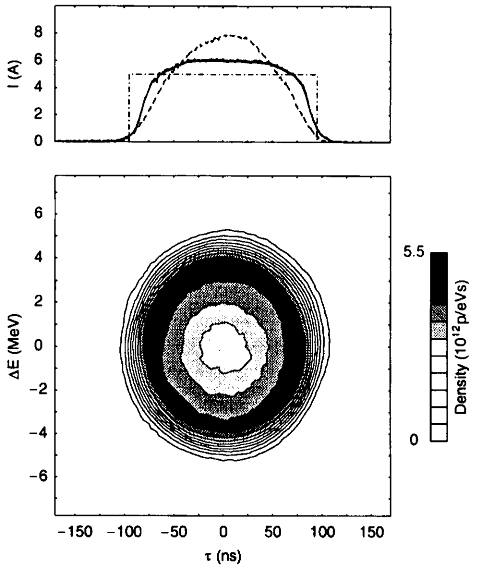

FIGURE 3. Tomographic reconstruction of the phase after redistribution of phase space surfaces.

SUMMARY AND OUTLOOK

New methods to create hollow bunches by gymnastics of a double harmonic RF system have been presented. One method based on redistribution of phase space surfaces has been tested successfully at the PSB. The aim is to alleviate limitations due to direct transverse space charge forces in a receiving synchrotron (in our case the PS).

The next step is to verify that the performance of space charge limited beams is indeed improved when the beam is transferred with hollow distribution in the longitudinal phase space.

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