CREATION OF HOLLOW BUNCHES BY REDISTRIBUTION OF PHASE SPACE SURFACES

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Abstract

The creation of hollow bunches in longitudinal phase space, in order to decrease the peak current and hence the transverse direct space charge forces, is an old idea. A new method to create such a hollow distribution at high energy has been simulated and tested experimentally at the PS Booster synchrotron. It is based on a redistribution of surfaces in the longitudinal phase space by using a double harmonic RF system. During the process, the beam is transferred from one second harmonic sub-bucket to another. Low density phase space surfaces from the periphery and high density regions from the centre are exchanged, leading to flat profiles, even after switching off the second harmonic RF system. During the process, the peak current is temporarily increased, which makes it suitable only to improve the situation in a receiving machine (in our case the PS) after transfer. In practice, the set-up of this new scheme turned out to be fast and simple and to yield reliable and reproducible results.

1 INTRODUCTION

It is an old idea [1] to create "hollow bunches" in longitudinal phase to fight performance limitations due to direct transverse space charge forces. The aim is to reduce the peak current for a given total bunch length and intensity, in order to reduce the incoherent (Laslett) tune shift. This can be achieved by shaping the density distribution in the longitudinal phase space. The optimum is achieved with a lower density in the centre and a higher density at the periphery.

Recent work [2] on hollow bunches at the CERN Booster Synchrotron (PSB) was not motivated by limitations in the machine itself (a double harmonic RF system is available in the PSB for bunch flattening), but aims to alleviate limitations due to direct space charge after transfer to the receiving PS machine, where no double harmonic RF system is available. Especially, high intensity beams (double batch injection for LHC or CNGS) kept a long time at low energy in the PS are expected to profit, if they are transfered with a hollow distribution in longitudinal phase space. For this application, it does not matter any more at which moment in the PSB cycle the hollow distribution is created. It can be done as well at high energy, where space charge effects are less critical, and as already attempted in reference [3].

In this paper, a new method to create hollow bunches, based on RF gymnastics with a double harmonic RF system[6], is presented. In practice, it was simple to implement the method and the results were reliable and very reproducible. It should be emphasised that this scheme will only alleviate space charge effects after transfer to a receiving machine without a double harmonic RF system for bunch flattening. The principle, i.e. redistribution of phase space surfaces, is explained in section 2. Results of simulations with the aim to determine appropriate RF parameters, are given in sections 3. Practical experience from machine experiments at the PSB are reported in section 4.

2 PRINCIPLE

With a double harmonic (e.g. harmonics 1 and 2 in our case for the PSB) RF system, one may create a double-bucket sub-structure inside the first harmonic buckets (Figs. 1 and 2). This case is typical, if the second harmonic is used for bunch lengthening and flattening with a relatively high voltage. The double-bucket is asymmetric (one smaller and one larger bucket), if the phase between the two RF systems is different from π. A situation, where most of the beam is contained in one large sub-bucket and another one is just created (Fig. 2 after 10 ms), is the starting point of the redistribution process. Then, the RF parameters are adjusted such that the large bucket shrinks and releases phase space surfaces, which start to surround the two buckets. The initially small bucket grows and captures these surfaces. Along the process, phase space is transfered from one sub-bucket to the other and, on that occasion, surfaces from the periphery and from the centre are exchanged. Thus, low density from the periphery ends up in the centre and vice versa.

The aim is to rearrange phase space surfaces quasi-adiabatically (as far as possible) and without any blow-up in the sense that no empty phase space is mixed in. Thus the total longitudinal emittance (and bunch length) is preserved. The RMS emittance however increases unavoidably.

3 SIMULATIONS

Simulations with the aim to determine RF parameters, appropriate for redistribution of phase space surfaces, have been made for a beam on a flat-top (protons with a kinetic energy of 1.4 MeV). Therefore the equations of motion :

$$
\begin{aligned}
\frac{d}{dt}\tau &= \frac{\eta}{\beta^2\gamma E_r}\,\Delta E \quad \text{and} \\
\frac{d}{dt}\Delta E &= \frac{q}{T_0}\left[V_1(t)\sin\left(2\pi\frac{\tau}{T_0}-\phi_1(t)\right)+\right. \\
&\qquad \left. V_2(t)\sin\left(4\pi\frac{\tau}{T_0}-(2\phi_1(t)+\phi_{21}(t)\right)\right]
\end{aligned}
$$

neglecting space charge forces, have been integrated numerically. Here β and γ denote the relativistic factors, η the momentum slip factor, E_r and q the rest energy and the charge of a beam particle and T_0 the revolution period. The functions V_1, V_2, ϕ_1 and ϕ_{21} describing the voltages and phases of the RF system, are given at some points and interpolated linearly in-between. The functions used for the simulation shown here are given in Fig. 1. It should be noted that the phase ϕ_1 of the principal harmonic RF system cannot be controlled directly (and is affected e.g. by feedback loops), but plays only a minor role and is taken into account for completeness. In fact, as long as the process is sufficiently adiabatic and the function ϕ_1 smooth, the result of the redistribution process does not depend significantly on the detailed form of ϕ_1. This has been verified by running the simulations with different shapes of the function $\phi_1(t)$.

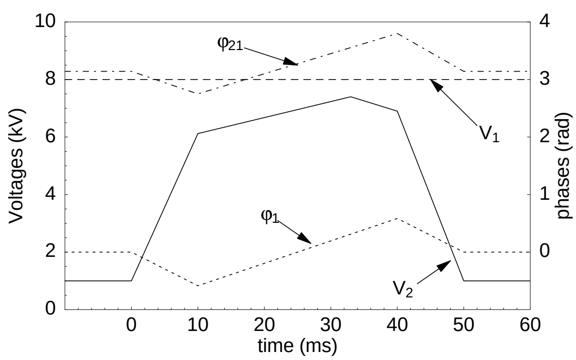


Figure 1: RF parameters versus time as used in the simulations.

Phase space plots during the resulting redistribution process are shown in Fig. 2. Different shades (and colours, if viewed with a device rendering colours) are used to plot particles initially in the centre or in the periphery, in order to facilitate the visualisation of the process.

During the first 10 ms, the phase difference $\phi_{21}(t)$ and the voltage $V_2(t)$ are ramped to end up with an appropriate double-bucket sub-structure. The situation after 10 ms is just after creation of the two bucket structure and corresponds to the beginning of the redistribution. The final density at the centre is determined by the location where the small bucket is created. Thus, the "hollowness" of the final result may be adjusted. The larger the large bucket is (larger phase excursion of ϕ_{21} and voltage V_2) at the creation of the double-bucket structure, the lower is the density at the centre at the end of the RF gymnastics.

The redistribution itself takes place between times 10 ms and 40 ms (see Figs. 1 and 2). The RF parameters are adjusted such that the initially large bucket shrinks and the initially small one grows. The total acceptance of the two sub-buckets together is larger at the end of the process. The aim is to mix some low density areas with large oscillation amplitudes with the high density from the core.

During the last 10 ms, the RF parameters are brought back to the initial values.

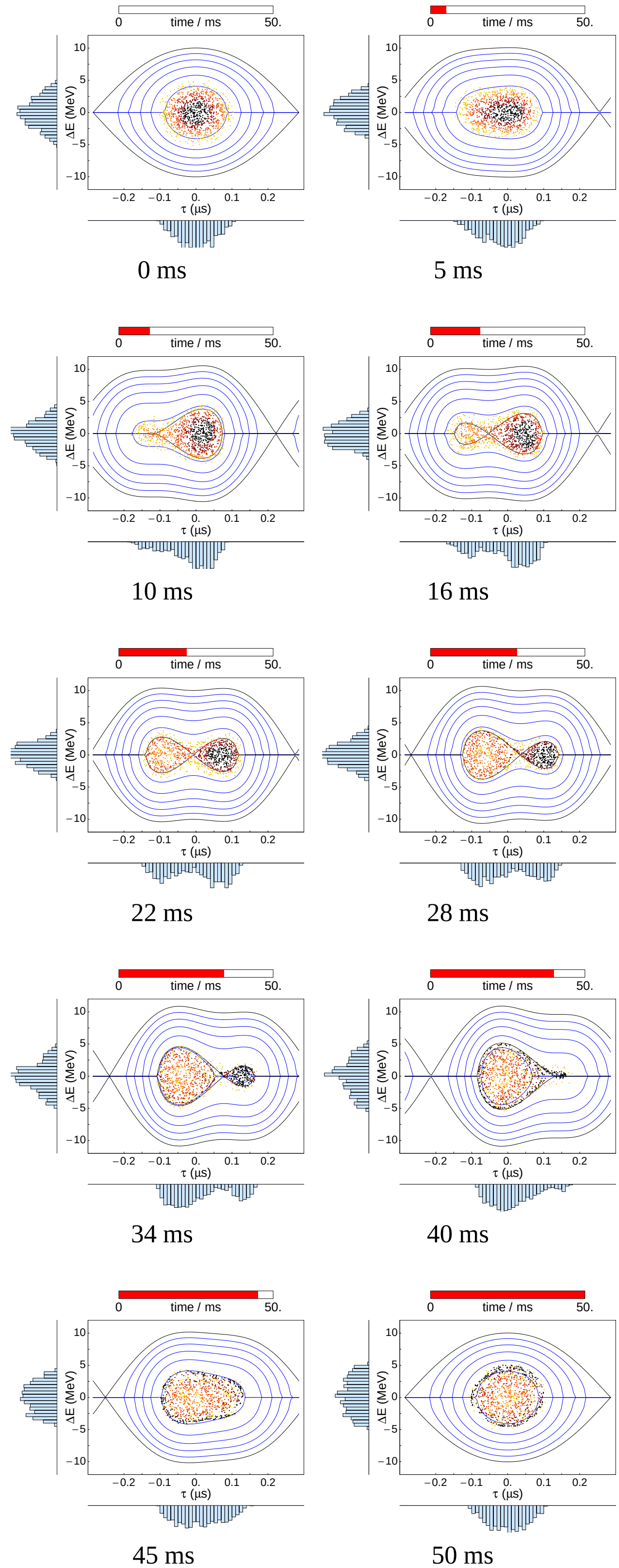
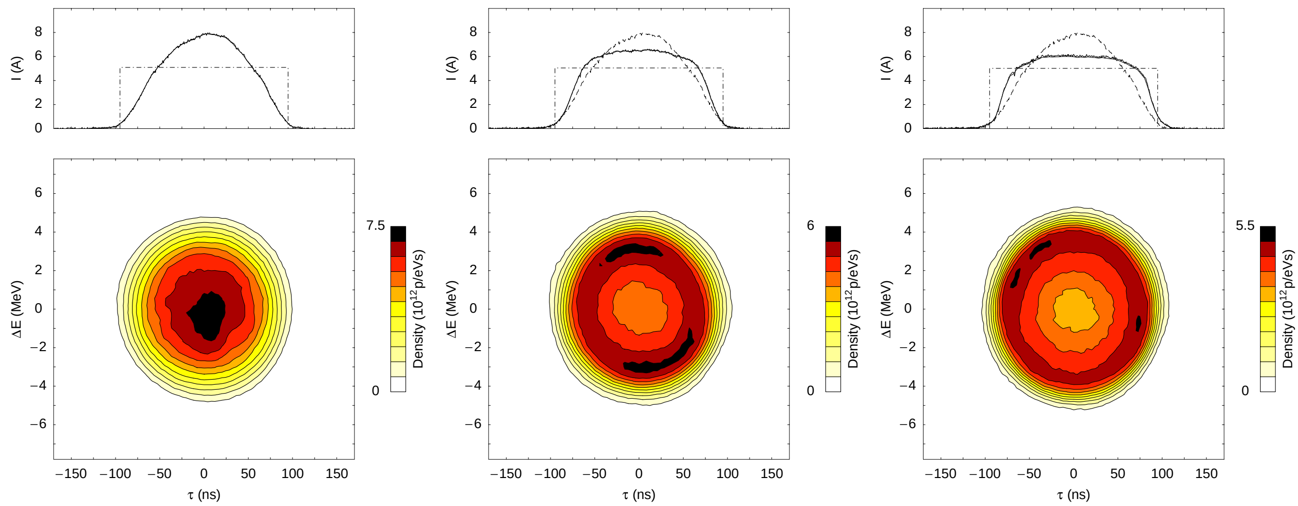


Figure 2: Redistribution of phase space surfaces to create hollow bunches. Simulated phase space portraits at different times during the process, with RF parameters versus time plotted in Figure 1.



(a) (b) (c)

Figure 3: Tomographic reconstructions of the density in longitudinal phase space without (a) and after (b and c) redistribution of surfaces.

4 EXPERIMENTAL RESULTS

During machine experiments, the method has been tested successfully. First tests have been done on a flat-top with increased length. After solving small technical problems, hollow bunches were obtained very quickly. After a short time, this new method for creating hollow bunches has been tested experimentally on the high energy part of the acceleration with success. The advantage of doing these RF gymnastics during the ramp is that the total length of the cycle is not increased and that the whole process may last longer, thus improving adiabaticity. The creation of hollow distributions in longitudinal phase space was very very reliable and reproducible.

Tomographic reconstructions [4, 5] of the density in the longitudinal phase space without and with redistribution are shown in Fig. 3 for bunches containing about 6×10^{12} protons. One notes that hollow distributions have been obtained without significant blow-up of the total emittance. The profiles plotted on top of the images show the decrease in peak current (in Fig. 3 (b) and (c) the profile obtained for a normal bunch without redistribution are plotted as well as dashed line for comparison). Comparison of Fig. 3 (b) and (c) shows that the resulting density distribution may be shaped to a certain extent by appropriate choice of phase ϕ_{21} and voltage V_2 at the beginning of the redistribution.

No intensity limitations (up to 8×10^{12} protons in one bunch) have been observed.

5 SUMMARY AND OUTLOOK

A new method, based on gymnastics with a double harmonic RF system, to create hollow bunches in longitudinal phase space is proposed, simulated and tested experimentally. The motivation is to alleviate performance limitations due to direct transverse space charge forces after transfer in a receiving synchrotron (in our case the CERN PS), where no other means for bunch flattening is available. During machine experiments in the PS Booster, this new method worked well and reliably after a short set-up time. The next step, planned for the year 2002 run, is to transfer these hollow bunches to the PS and to verify that the performance for beams with a large incoherent tune shift is indeed improved.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] J.P. Delahaye, G. Gelato, L. Magnani, G. Nassibian, F. Pedersen, K.H. Reich, K. Schindl and H. Schönauer, “Shaping of Proton Distribution for Raising the Space-charge of the PS Booster”, 11^{th} Int. Conf. on High-Energy Accelerators, Geneva, 1980.

[2] A. Blas, S. Hancock, M. Lindroos, S. Koscielniak, “Hollow Bunch Distributions at High Intensity in the PS Booster”, EPAC’00, Vienna, June 2000.

[3] R. Garoby, S. Hancock, “New Techniques for Tailoring Longitudinal Density in a Proton Synchrotron”, EPAC’94, London, 1994.

[4] S. Hancock, M. Lindroos, E. McIntosh, M. Metcalf, “Tomographic measurements of longitudinal phase space density”, Computer Physics Communications, 118 (1999).

[5] S. Hancock and J.-L. Sanchez Alvarez, “A Pedestrian Guide to online Phase Space Tomography in the CERN PS Complex”, CERN PS/RF Note 2001-010 (2001).

[6] C. Carli, “Creation of Hollow Bunches using a Double Harmonic RF System”, CERN/PS 2001-073 (AE).