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Creation of Hollow Bunches using a double harmonic RF System

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Abstract

The main motivation for the creation of hollow bunches in the PSB is to increase the bunching factor at transfer to the PS. Due to the reduction of the peak current and direct transverse space charge forces, one expects less blow up and losses at low energy in the PS. Thus, it does not matter when the hollow distribution in longitudinal phase space is created in the PSB cycle. We propose methods involving the h=1 and h=2 RF systems available in the PSB. The first method is based on controlled blow up by recombination of the bunch in one bucket, with another empty bucket. By appropriate adjustment of the phase between the two RF systems, more empty phase space can be inserted close to the centre creating a hollow distribution. The second method is based on a redistribution of phase space. The beam is transfered from one h=2 sub-bucket to the other and, during that process, regions from the centre with high density and from the periphery are exchanged. Simulations of both methods, based on tracking of particles in the longitudinal phase space, are presented. The second method has been set up successfully at the PS Booster. A significant decrease of the peak current has been achieved, while keeping the bunch length approximately constant.

1 Introduction

The basic motivation behind the search for bunches with a lower density in the centre of the longitudinal phase space is to obtain flatter bunch shapes and thus a higher bunching factor (defined as the mean current divided by the peak current) for a given bunch length. This in turn leads to smaller transverse direct space charge forces and thus to a smaller Laslett tune shift. The motivation of the first attempts [1] to create hollow bunches [1)] in the PS Booster was to decrease the transverse space charge detuning in the Booster itself, in order to accelerate higher intensities. The dual harmonic RF system was later installed in order to flatten the bunch shapes and, thus, only little could be gained by additional RF manipulations producing hollow phase space distributions. In practice, an increase of the intensity accelerated in the PS Booster due to hollow bunches seems out of reach.

Thus the motivation for renewed interest [2] in the creation of hollow bunches has shifted to the low energy behaviour of beams transfered to the PS synchrotron. In principle, all beams with a large direct space charge (Laslett) tune shift (high intensity and/or high brilliance) are expected to profit from an increase of the bunching factor, especially in conjunction with double-batch injection (for LHC and CNGS). For this application, it does not matter when the hollow bunches are created in the Booster cycle. They can be created at higher energy as already attempted in reference [3]. In this report, new methods using the dual harmonic RF system (combining the first $h = 1$ and the second $h = 2$ harmonic) to create hollow bunches at high energy in the PS Booster are presented. Both methods have been simulated by tracking beam particles on the 1.4 GeV flat-top using a simple Mathematica program neglecting direct space charge forces. One method has been applied successfully in practice.

The first method, outlined in Section 2.1, is in fact a controlled blow up, based on the recombination of a bunch with an empty bucket, similar to the scheme in reference [4]. By coalescing the two buckets in an asymmetric manner by acting on the phase of the second harmonic RF system, more empty phase space can be added at the centre. This procedure has not been applied for practical reasons. Complicated RF gymnastics are required and it leads to longitudinal blow-up.

Another method, described in Section 2.2, aims to redistribute surfaces in the longitudinal phase space. The resulting procedure is simpler in the sense that it requires less RF gymnastics. It is also better adapted to the present situation at the Booster, because the conventional blow-up works very well and leads to the needed longitudinal emittances, but, on the other hand, acceleration without blow-up leads to low performance and large shot-to-shot variations. This method for the creation of hollow bunches has been applied successfully in practice. The time needed for the set-up was surprisingly short and the procedure turned out to be very robust. The experimental observations and the experience gained are reported in Section 3.

2 Principle and Simulations

In the simulations, the equations of motion :

$$\begin{aligned} \frac{d}{dt}\tau &= \frac{\eta}{\beta^2\gamma E_r}\,\Delta E \\ \frac{d}{dt}\Delta E &= \frac{1}{T_0}\left[V_1(t)\sin\left(2\pi\frac{\tau}{T_0}-\phi_1(t)\right)+V_2(t)\sin\left(4\pi\frac{\tau}{T_0}-(2\phi_1(t)+\phi_{21}(t))\right)\right] \quad , \end{aligned}$$

neglecting direct space charge forces, are integrated numerically, using a simple Mathematica program. Here β and γ denote the relativistic factors, η the momentum slip factor, E_r the rest energy of a beam particle and T_0 the revolution period. The functions V_1, V_2, ϕ_1 and ϕ_{21} describe the voltages and phases of the RF system. The time-dependence of these functions has been adjusted to the case to be studied. It should be noted that the phase ϕ_1 of the principal RF system is difficult to control and to predict in practice (because it depends on loops). But, if the process is slow and quasi-adiabatic, ϕ_1 plays only a minor role.

[1)] In this context, the term hollow bunches denotes a longitudinal phase space distribution with lower intensity in the centre and higher densities at large amplitudes. However, the density in the centre must not be too small, i.e a donut shaped phase space distribution with no particles at the centre must be avoided, because it leads to instabilities [2].

2.1 Blow up by recombination of a bunch with an empty bucket

The procedure proposed in this section was inspired by reconstruction of bunch splitting using tomography [5] of the longitudinal phase space. During bunch splitting, one aims to transfer phase space surfaces in a quasi-adiabatic manner. Thus, in principle, the process can be reversed : in fact the phase space portraits obtained by tomography have to be mirrored, in order to achieve that the particles move in the right direction. Neglecting direct space charge forces, one could imagine recombining a bunch in one bucket with an empty bucket, an idea already studied independently in [4]. If, furthermore, the relative phase between the second harmonic and the first harmonic RF system are adjusted in an appropriate manner, then the asymmetric process can provide different blow-ups, and more empty phase space can be inserted in the centre to achieve hollow bunches.

A case producing large blow-up and lower phase space density in the centre has been simulated and is shown in Figures 1 and 2. The time-dependence of the RF functions $V_1(t)$, $\phi_1(t)$, $V_2(t)$ and $\phi_{21}(t)$ is given in Figure 1. The form of the function $\phi_1(t)$ is not important for the process. This has been verified by tracking, using constant phases ϕ_1, leading to very similar results. Phase space portraits during the blow-up process are given in Figure 2. The starting point reflects the standard situation in the PSB for a beam with a small longitudinal emittance of $\epsilon_l = 4\pi\sigma_\tau\sigma_{\Delta E} = 0.8$ eVs before extraction, with a Voltage of 8 kV for the first harmonic RF system and a small Voltage of about 1 kV (needed for good performance and reproducible bunch shapes) on the second harmonic system in anti-phase, i.e. $\phi_{21} = \pi$. Then, the phase $\phi_{21}(t)$ between the two RF systems is shifted and the voltage of the 2^{nd} harmonic RF system is increased to form a second bucket outside the area occupied by the beam. After 14 ms the second bucket starts to form. Then the voltage of the $h = 2$ RF system is further raised and the phase shifted in order to increase the size of the second empty bucket. Both parameters are adjusted such that the bucket with the beam is just large enough to contain the beam, and the empty bucket contains the empty phase space to be inserted. From this situation after about 23 ms, the two buckets are slowly recombined. The more synchrotron revolutions the process lasts, the finer is the spiral structure obtained in the phase space. By adjusting the phase $\phi_{21}(t)$ appropriately while decreasing the voltage $V_1(t)$, one can insert less empty phase space in the periphery of the “recombined” bunch and more in the centre. The two buckets are recombined after 50 ms (i.e. there is no double bucket structure inside the $h = 1$ bucket any more), but the phase space is still distorted by the large voltage V_2 provided by the 2^{nd} harmonic RF system. Finally, the voltage and phase difference are brought back to the initial values appropriate for extraction. This situation is obtained after 60 ms in the simulation. Inspecting the phase space after 60 ms in Figure 2, one notes that the spiral structure is rather fine in the outer regions, but rough at the centre. The reason is that the two buckets collapse fast at the end of the merging process. A way to overcome this is to change the RF parameters faster at the beginning and more slowly towards the end of the merging process. The results of such a scheme are shown in Figures 3 and 4. Similar blow-up schemes have already been studied earlier and independently [4], but have not been published.

Direct space charge forces have been neglected for the simulations presented. Potential distortion due to direct space charge forces is only a small correction to the potential provided by the RF system. Thus, the effect of direct space charge forces can be compensated by small readjustments of RF parameters.

This scheme has not been tested experimentally for the creation of hollow bunches in the PSB, because it necessitates rather complicated RF gymnastics, and leads to excessive blow-up, not compatible with the present situation at the PSB.

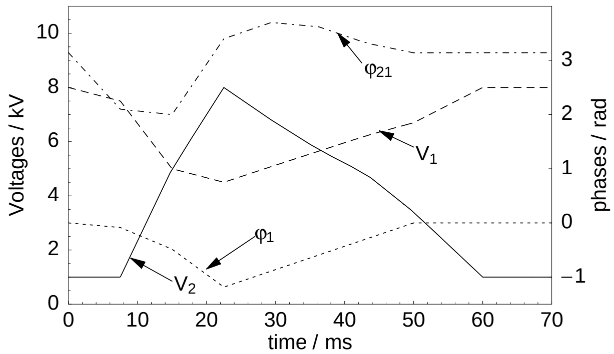
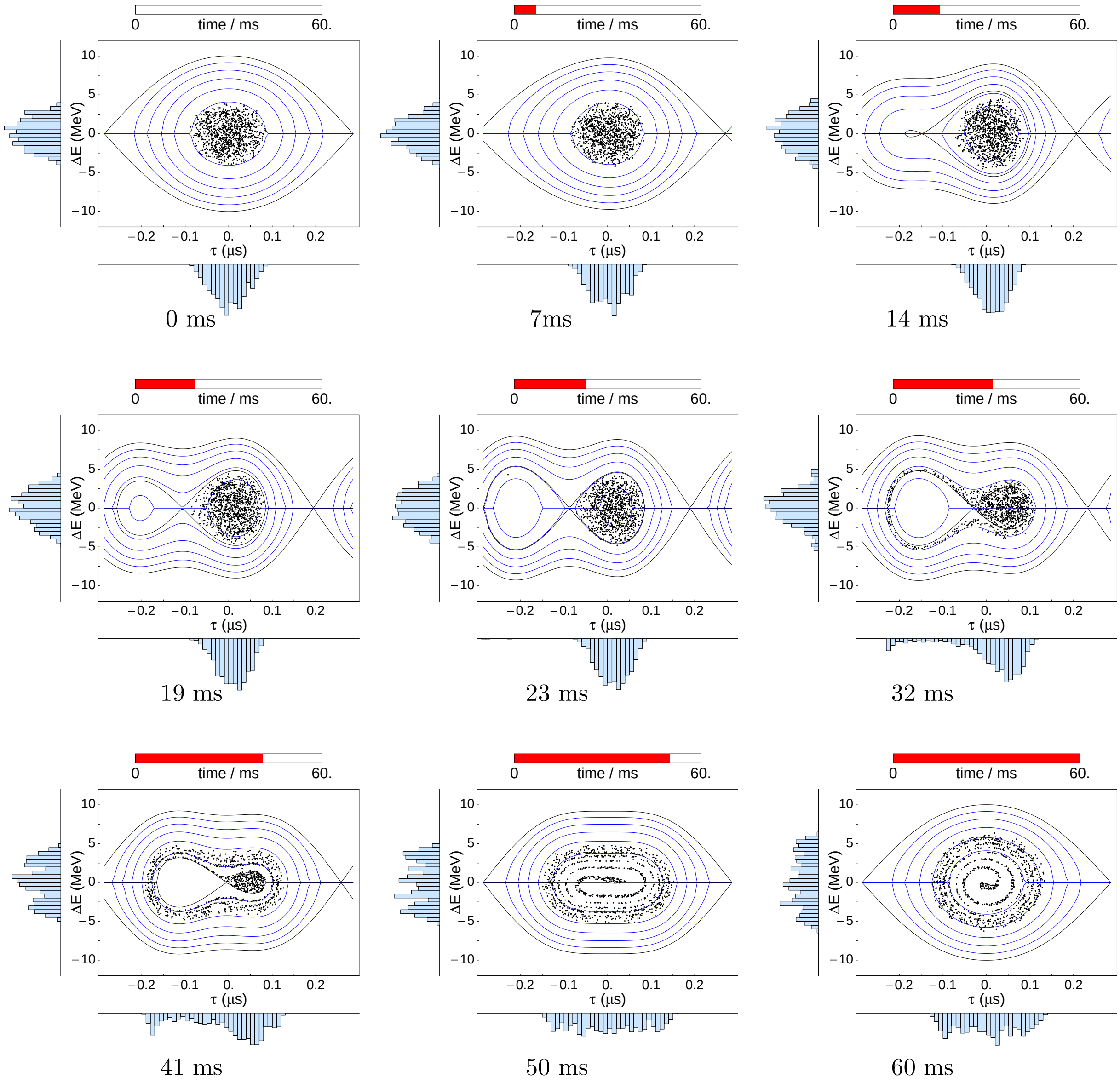


Figure 1: *Voltages and phases used for the simulation of longitudinal blow-up.*



0 ms

7ms

14 ms

19 ms

23 ms

32 ms

41 ms

50 ms

60 ms

Figure 2: *First attempts to simulate blow-up by recombination of a bunch with an empty bucket. Simulated phase space portraits at different times during the process, with the RF functions plotted in Figure 1.*

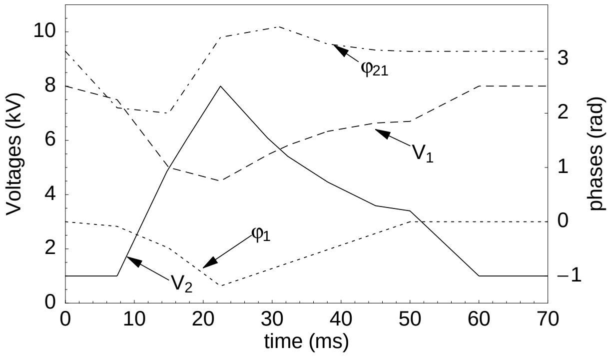
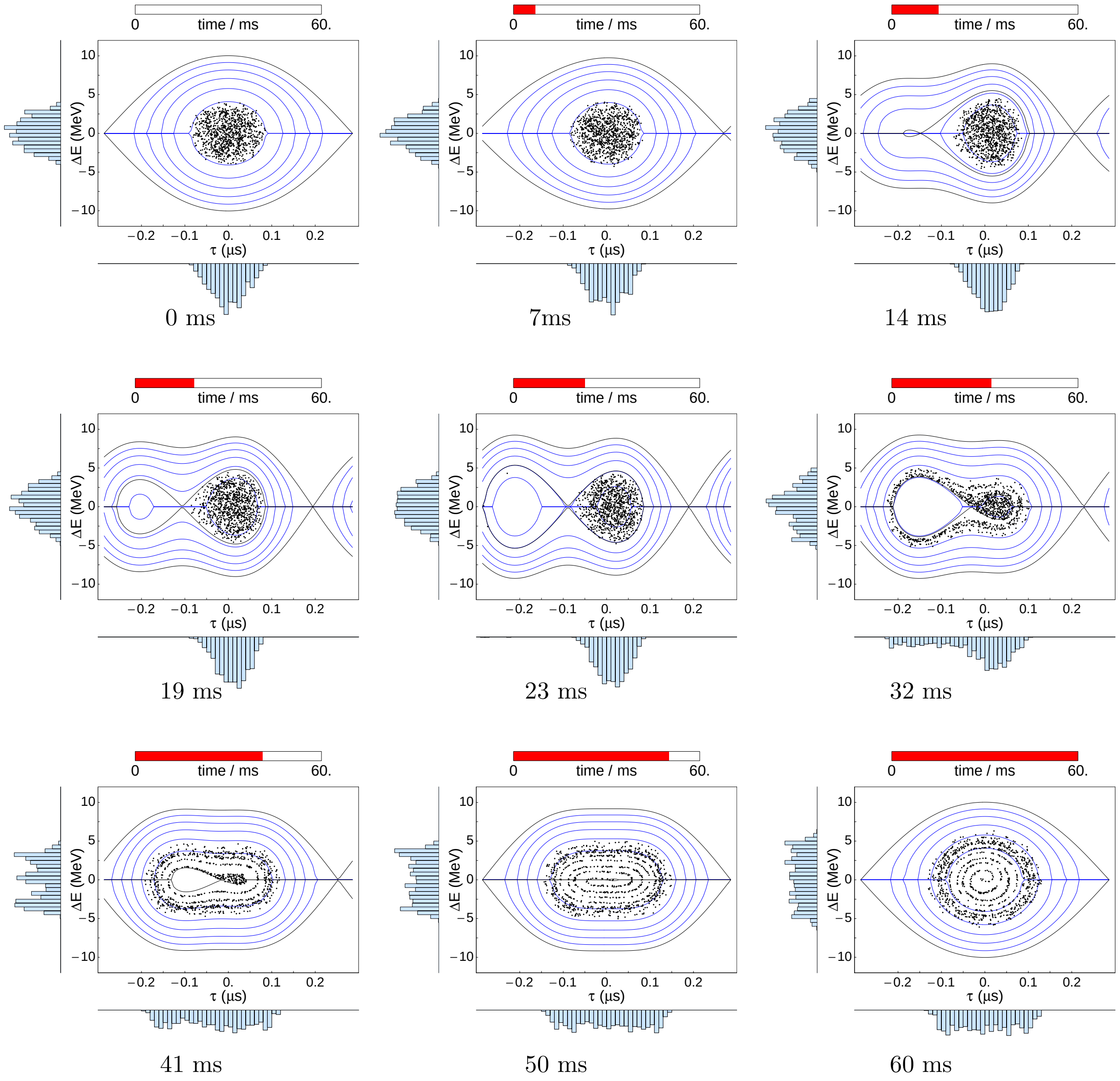


Figure 3: *Voltages and phases used for the simulation of longitudinal blow-up with improved adiabaticity at small amplitudes.*



0 ms

7ms

14 ms

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23 ms

32 ms

41 ms

50 ms

60 ms

Figure 4: *Blow-up by recombination of a bunch with an empty bucket with improved adiabaticity at small amplitudes. Simulated phase space portraits at different times during the process, with RF parameters versus time plotted in Figure 3.*

2.2 Hollow bunches by redistribution of phase space surfaces

When recombining a bunch with an empty bucket, one has to be careful creating the second bucket outside the bucket populated by the bunch. This is achieved by shifting the phase ϕ_{21} between the two RF systems before increasing the voltage of the 2^{nd} harmonic RF system - see situation after 14 ms in Figure 2. If the longitudinal emittance is large and/or the phase ϕ_{21} has not been shifted far enough away from π, the small second sub-bucket is created inside the beam. This situation, depicted in Figure 6 after 10 ms, is the starting point for the method to create hollow bunches described in this section. During the redistribution process, the RF functions (mainly the phase ϕ_{21}, but also the voltage V_2) are adjusted such that the new bucket grows and captures particles surrounding it, whereas the initial bucket shrinks and releases particles. During the redistribution process, phase space surfaces, released by the initial bucket, start to surround the two buckets and, finally, end up captured in the new bucket. The procedure goes on, until the initial bucket disappears. Phase space surfaces with low density from the periphery of the initial bucket are captured first, ending up in the centre of the new bucket. High density regions, from the centre of the initial bucket, are released at the end of the process, and are captured in the periphery of the new bucket. Furthermore, one can slightly increase the total acceptance of the two sub-buckets, by adjusting the voltage V_2 along the process, and mix phase space surfaces with low density from the surroundings with the dense core.

A simulation of the whole process is shown in Figures 5 and 6. Voltages and phases inserted in the equations of motion are shown in Figure 5. It has been verified by tracking with other shapes for the function $\phi_1(t)$, that the phase of the first harmonic RF system is, once again, not crucial for the process. For the phase space plots shown in Figure 6, different shades (and colours if viewed with a device rendering colours) are used to represent particles with different initial synchrotron oscillation amplitudes in order to visualize the exchange between phase space surfaces with small and large amplitudes. The tracking simulations again start with typical parameters at extraction from the PSB, with a longitudinal emittance $\epsilon_l = 4\pi\sigma_\tau\sigma_{\Delta E} = 1.2$ eVs. The phase of the $h = 2$ RF system is shifted and the voltage is raised. The redistribution process starts when the second bucket just forms, i.e. at the situation after 10 ms. The phase space density at the centre, after the completion of the redistribution process, is given by the density at the location where the second bucket forms. Thus, the "hollowness" of the bunch can be chosen by adjusting that location by appropriate choice of phase and voltage at the start of the redistribution process. Then, the phase $\phi_{21}(t)$ is shifted (in a direction opposite to the one of the previous shift) and the voltage V_2 is slightly adjusted, resulting in an increase of the size of the new bucket and a decrease of the size of the initial one. Particles released by the initial bucket are captured by the second one. In addition, the voltage of the 2^{nd} harmonics RF system is raised in order to increase the total surface of the two buckets. Then some phase space with low density outside the two buckets is captured as well, and mixed with surfaces of high density from the core of the initial bunch. The redistribution process ends when the initial bucket disappears, i.e. after 40 ms in the simulation. During the last 10 ms the RF system is brought back to the initial conditions.

This method is well adapted to the present situation at the PSB (conventional blow-up working well, but poor performance without blow-up) and necessitates only rather simple RF manipulations.

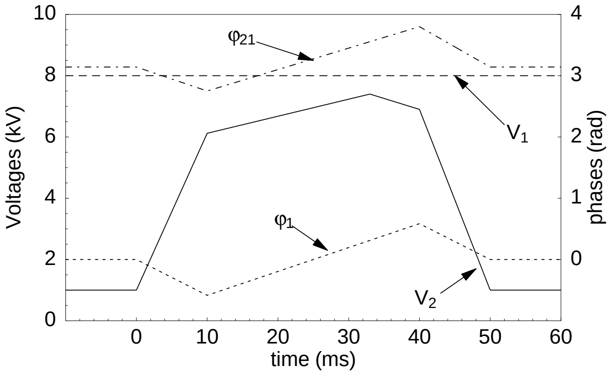
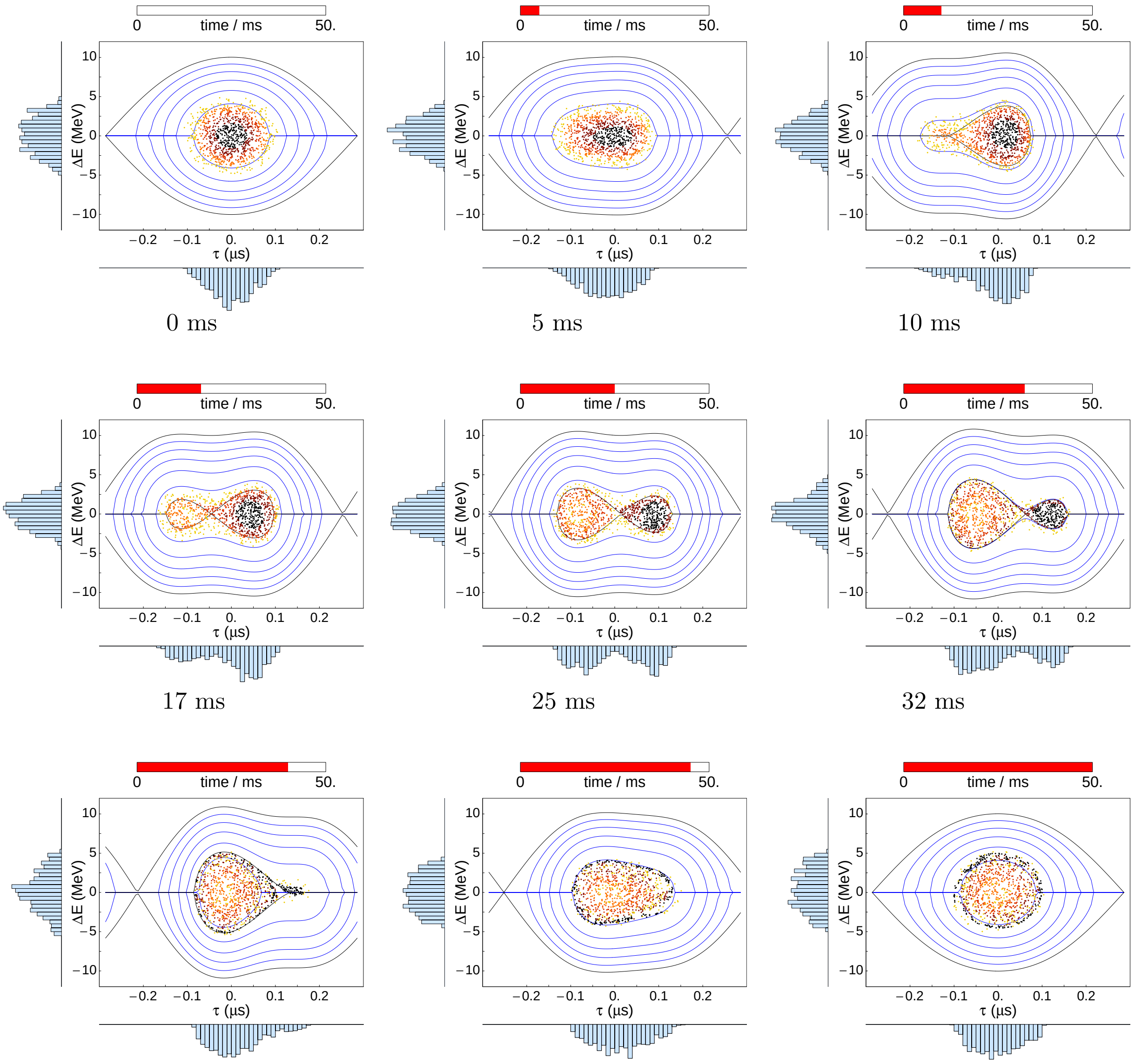


Figure 5: *Voltages $V_1(t)$ and $V_2(t)$ and phases $\phi_1(t)$ and $\phi_{21}(t)$ used for the simulation of redistribution in the longitudinal phase space.*



0 ms

5 ms

10 ms

17 ms

25 ms

32 ms

40 ms

45 ms

50 ms

Figure 6: *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 5.*

3 Experimental Results

The creation of hollow bunches by redistribution of surfaces in the longitudinal phase space has been tested in a machine experiment. In a first step, the method was applied to beam on a plateau at 1.4 GeV, as assumed in the simulations presented in section 2.2. Therefore, a special cycle with a flat-top length increased by 100 ms was set up. The conversion coefficient between the programmation of the GFA [2] and the resulting phase offset between the two RF systems was not known initially and had to be calibrated. Therefore, the phase between the two RF systems was shifted while keeping the voltages of both systems at 8 kV. The phase between the $h = 1$ and the $h = 2$ RF system is about π, when the two equal bunches are present. With the parameters of the PSB (longitudinal emittance $4\pi\sigma_\tau\sigma_{\Delta E} \approx 1.2$ eVs) the transition between one and two bunches takes place at a phase of about $\phi_{21} = \pi \pm 1.2$. After this rough calibration, the voltages V_1 and V_2 and the phase ϕ_{21} between the two RF systems were programmed to follow the functions used in the simulations. The phase ϕ_1 is not accessible (e.g. by programmation of a GFA), but is a result of feed-back loops. However, if the process is quasi-adiabatic, this parameter is not important. After programmation of the RF GFAs and without any further adjustment, the effect of hollow distributions on the bunch shape was immediately observed.

Since the cycle length of the PSB is limited, the duration of the redistribution process was only about 50 ms, as assumed in the simulations. But, in principle, the same process is feasible during the acceleration and may last longer. This was set up experimentally, in order to avoid an increased cycle length and to decrease effects due to non-adiabaticity. The duration of the whole process was lengthened to 160 ms (30 ms to create the 2nd bucket + 100 ms for the redistribution + 30 ms to end up with the setting for transfer). The results, obtained for ring 2 of the PSB, are compared to the case without redistribution to create hollow bunches in the tomographic reconstructions and profiles shown in Figure 7. The lower density at small synchrotron oscillation amplitudes is clearly visible in the reconstructed [6] phase space distributions shown in Figure 7, b and c. The phase space density at the centre of the phase space has been adjusted to different values (by larger (smaller) voltages and phase excursions of the $h = 2$ RF system for Figure 7 b (c)) to demonstrate that the bunch flattening can be varied in a certain range. For comparison, the density distribution obtained with a standard programmation of the RF system is shown in Figure 7a.

The bunch profiles are shown on top of the tomographic reconstructions in Figure 7. The dot-dashed square denotes a “perfect” profile, i.e. giving the maximal bunching factor 0.332 for a bunch length of 190 ns. For comparison, the profile obtained without redistribution of phase space surfaces is plotted as a dashed line in Figure 7, b and c. The increase in bunching factor (up to 40 %) is clearly visible. The increase in bunch length, and thus the increase in total longitudinal emittance, is negligible. The increase of the RMS longitudinal emittance is inherent to the process and is caused by the desire to have hollow bunches.

The creation of hollow bunches has been demonstrated with different intensities up to 8×10^{12} protons in one ring and no limitations due to direct space charge have been observed.

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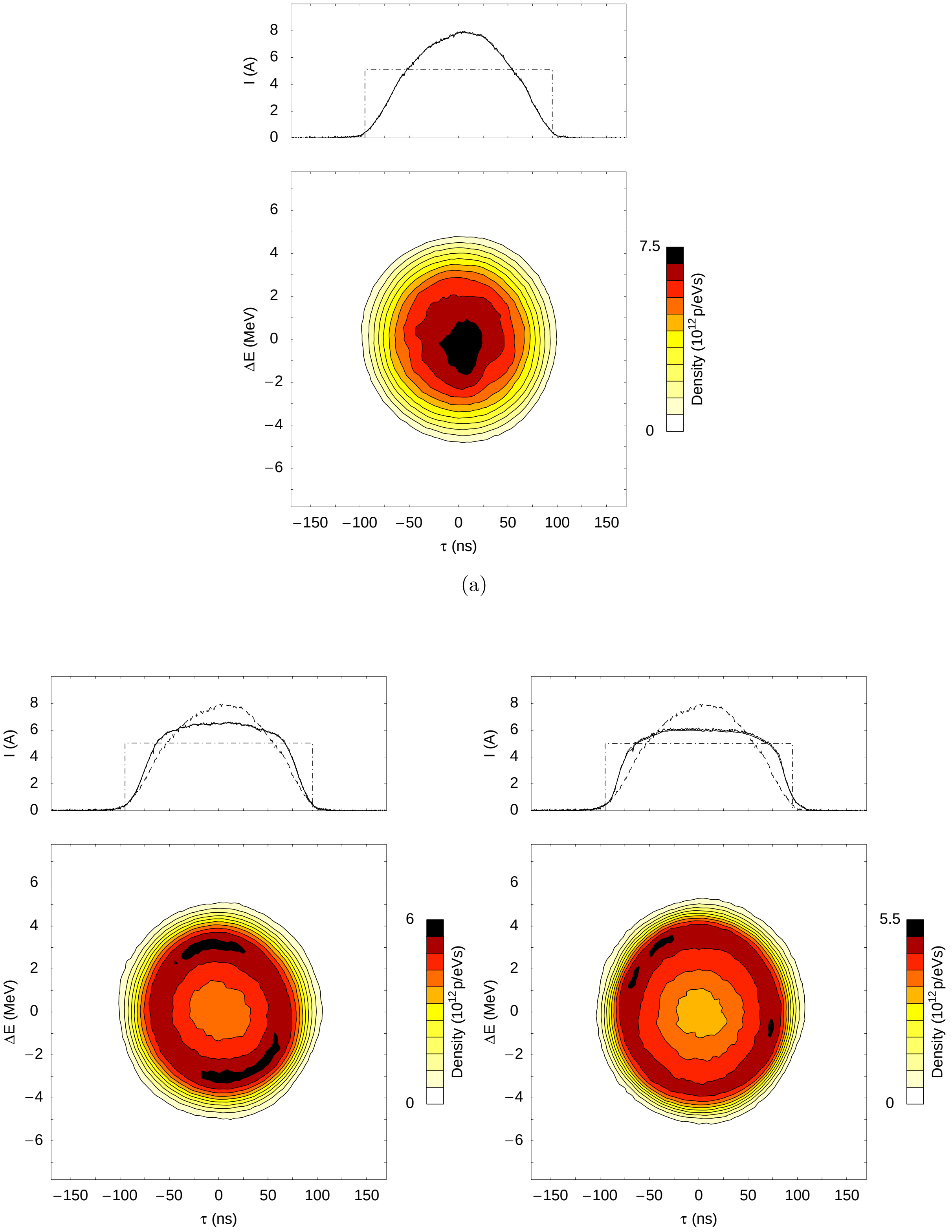
[2] Electronic devices, which execute previously programmed functions at their output. Those functions can be rather arbitrary functions of time.



(a)

(b)

(c)

Figure 7: Tomographic reconstruction of bunches without (a) and with (b and c) redistribution in the longitudinal phase space. The measurements reflect the situation after synchronization and 5 ms before extraction. The measurements have been done with about 6×10^{12} in one bunch in ring 2 of the PSB.

4 Conclusions

New methods for controlled blow-up and the creation of hollow bunches have been presented. Both methods have been simulated by tracking particles in the longitudinal phase space. One of the methods leading to hollow bunches with negligible blow-up has been tested in practice. After a short time needed for the set-up, a significant increase of the bunching factor has been achieved with good reliability and reproducibility. In practice, the method worked very well with high intensities (about 6×10^{12} protons in one ring). While, for the simulations, an increase of the length of the flat-top had been assumed, in practice the creation of hollow bunches has been demonstrated also during the high energy part of the acceleration.

The methods presented here are not suitable to create hollow distributions of high intensity beams at low energy in the PS Booster. During the processes, temporarily decreased bunching factors and increased maximal currents occur. This does no harm at high energy in the PS Booster.

The methods are not restricted to h=1 and h=2 RF systems, but could, in principle, be applied with higher harmonic RF systems at any accelerator. The only conditions is that a second RF system working at a suitable higher harmonic number is available.

Acknowledgements

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