HOLLOW BUNCH DISTRIBUTIONS AT HIGH INTENSITY IN THE PS BOOSTER

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Abstract

Bunches from the CERN PS Booster (PSB) with an improved bunching factor due to a hollow longitudinal distribution would facilitate the production of a high-intensity ($>7\times10^{12}$/bunch) proton beam needed for the future neutron time-of-flight facility. It would also provide a safety margin for the Large Hadron Collider beam, where a double-batch transfer is used in which the first PSB batch waits for 1.2 seconds at 1.4 GeV in the PS for the second one to arrive. Since the earlier reports of the successful acceleration of low-intensity hollow bunches in the PSB, theoretical studies of the Beam Transfer Function (BTF) have led to a greatly improved understanding of the stability requirements of such beams. In addition, an experimental study of the capture of hollow coasting beams has revealed that structure resulting from the linac acceleration process persists for a remarkably long time. Any inhomogeneity has to be smeared out and the degree of hollowness carefully adjusted by a controlled longitudinal blow-up before a reproducible, stable bunch can be created. A method has been developed for reliably creating hollow distributions of up to 8×10^{12} protons per bunch which have been routinely accelerated in the PSB.

1 INTRODUCTION

A first attempt to produce hollow longitudinal distributions in the PSB was hampered by the limited longitudinal acceptance of the existing h=5 rf system and by instabilities during acceleration[1]. The successful acceleration of flat-topped bunches in the PS[2] and the increase in acceptance due to the new h=1 PSB rf system has prompted a renewed effort. We have already reported the successful acceleration of low-intensity bunches in the PSB[3]. This paper describes further developments permitting the acceleration of high-intensity bunches.

The method (see Figure 1) is based on the deposition of high-harmonic, empty rf buckets at the centre of a debunched beam before rf capture. This results in a double-peaked energy spectrum, where the depth of the valley between the peaks can be controlled by the slew rate with which the empty buckets are swept into the beam. After capture and filamentation in the bucket of the fundamental rf system, an approximately annular distribution results. Low-intensity flat-topped bunches were made with a high slew rate, the low adiabaticity resulting in a shallow valley in the energy spectrum. After rf capture, the flattened bunches were readily accelerated to full energy.

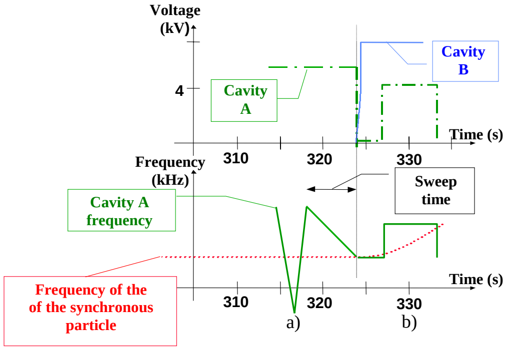

Figure 1: Basic rf manipulations for introducing empty buckets into a debunched beam. Cavity A is used (a) for the empty bucket deposition and (b) for the longitudinal blow-up. Cavity B is the main accelerating cavity.

For high-intensity bunches, the slew rate has to be decreased to permit larger empty buckets to be deposited. However, the resultant phase space distributions become unstable early during acceleration. This is shown by a strong dependence on the symmetry of the initial distribution and consequent pulse-to-pulse variability in the bunch shapes at extraction, making them unsuitable for transfer to the PS.

2 HOLLOW DISTRIBUTIONS

2.1 Stability

The stability of a longitudinal distribution can be studied with BTFs provided that an accurate description of the rf system and its feedback is available[4]. In Figure 2, BTFs are plotted for three different particle distributions[5]. To determine the stability of these distributions using the Nyquist criteria, the BTFs have to be calculated at point 2) with an open feedback loop. The BTFs at point 2) are shown in the middle-right plot in Figure 2 and it can be seen that case c) is unstable. Longitudinal space charge also has some effect on the distributions, but this is not included in our analysis.

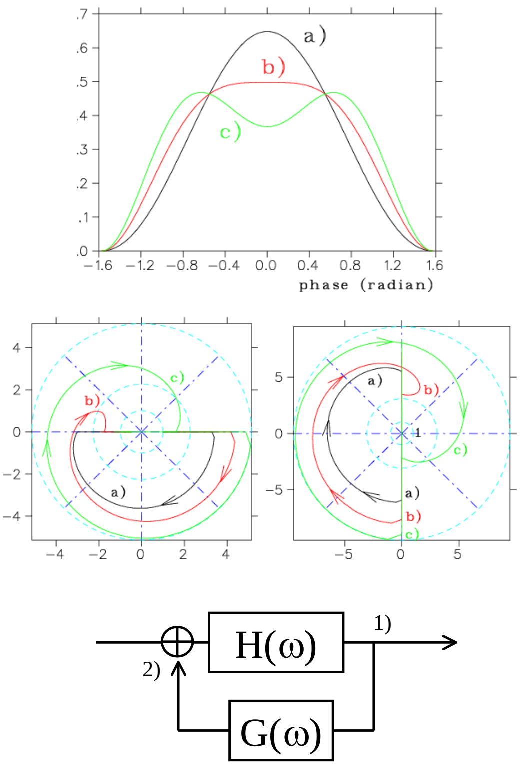

Figure 2: BTFs calculated for three different longitudinal particle distributions. The top plot shows the corresponding bunch shapes. The left-middle plot shows the BTFs at point 1) and the right-middle plot the BTFs at point 2).

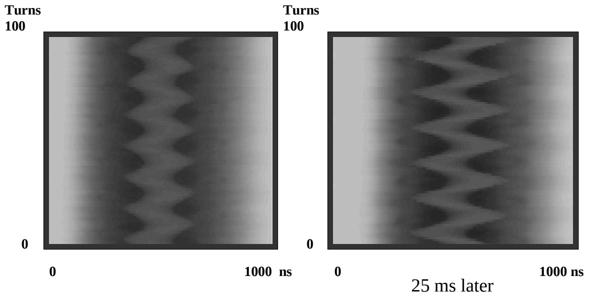

Figure 3: Development of an instability as the low-density central portion of a bunch is anti-damped. The plots consist of bunch profiles taken 25 turns apart plotted on the y-axis. On the x-axis, the intensity on a much shorter time scale along the bunch is represented as a grey-scale.

A more intuitive explanation is to consider a hollow distribution as comprising a small negative bunch superimposed on a larger positive bunch. The phase loop is made to damp the oscillations of a positive bunch and will, consequently, anti-damp the motion of a negative bunch. The outcome of this competition depends on the relative phase space density and the frequency response of the positive and negative bunches, and can mean instability. This is illustrated in Figure 3 where oscillations of a strongly hollow distribution increase over 25 ms. This bunch was eventually lost.

2.2 Influence of linac beam structure

Prior to injection into the PSB, the beam micro-structure is debunched by the action of a debuncher cavity and the linac transfer line. However, an apparently random residual structure is observed at PSB injection. It has been shown[6] that such “pockets” of empty phase space can be remarkably stable under conditions in which the tendency to debunch, due to momentum spread, is balanced against the focusing effect of space charge (for voids below transition energy). Such structure can occasionally leave unwanted regions of empty phase space in the debunched beam, which perturbs the empty bucket deposition (see Figure 4) and introduces asymmetry in the beam during capture. Sweeping the empty buckets through the entire energy range of the injected beam, before their final deposition at its centre, disrupts the balance that maintains the voids. Subsequent filamentation will homogenize any remaining linac structure, making the capture process reproducible.

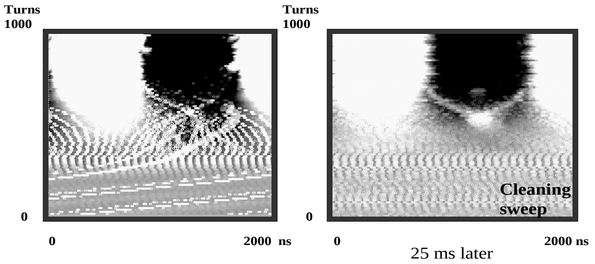

Figure 4: To the left, residual structure in the linac beam makes the production of flat-topped bunches non-reproducible. To the right, the frequency of a high-harmonic cavity is swept through the entire beam provoking the filamentation of any remaining structure.

2.3 Controlled blow-up

At high intensity, the deposition of small empty buckets is not sufficient to yield bunches that are flat over a reasonable portion of their length. However, depositing large empty buckets produces double-peaked bunches which are unstable.

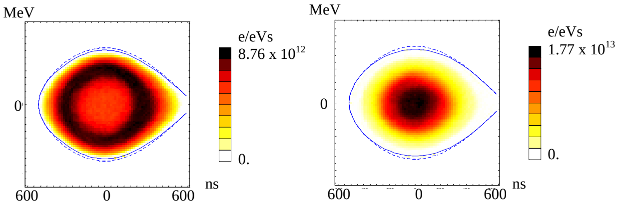

Figure 5: To the left, a flat bunch of 7.4×10^{12} protons and, to the right, a normal bunch of the same intensity. Note the different density scales.

The solution is to deposit large buckets and then to apply a controlled longitudinal blow-up just after capture, using the same high-harmonic buckets, but with their rf frequency at a fixed offset[7]. This drives some particles from the densest annulus in phase space back into the centre, allowing the flatness of the projected bunch shape to be tailored. The re-distribution also stabilizes the beam, making acceleration possible.

3 CONCLUSIONS

Flat-topped bunches of up to 8×10^{12} protons have been successfully accelerated in the PSB. A typical tomogram[8] of a hollow distribution is compared to a normal one in Figure 5. The corresponding bunch profiles and 2D density plots are shown in Figure 6.

The earlier reported problems of irreproducibility and instability have been overcome. The intensity now seems to be limited by the transverse incoherent space charge tune shift during rf capture. The strongly double-peaked bunch shape results in an initial large tune shift before the blow-up has flattened the bunch.

Dual-harmonic capture could be used to overcome this, but the BTF is then inherently unstable. Consequently, a hybrid process is under development in which the beam is captured with a dual-harmonic system but only the principal harmonic is retained throughout acceleration.

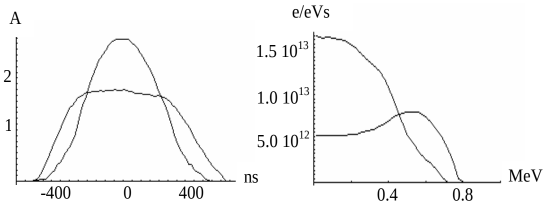

Figure 6: To the left, the measured bunch profiles of the two distributions of Figure 5. The bunching factor is improved from 0.32 to 0.49. To the right, the corresponding 2D density profiles.

REFERENCES

[1] J.P. Delahaye et al., "Shaping of proton distribution", Proc 11th Int. Conf. on High-Energy Accelerators, Geneva, pp.299-304 (1980).
[2] R. Garoby, S. Hancock, "New techniques for tailoring longitudinal density in a proton synchrotron", European Particle Accelerator Conf., London (1994).
[3] A. Blas, S. Hancock, S. Koscielniak, M.Lindroos, F. Pedersen, "New technique for bunch shape flattening", Particle Accelerator Conf., New York, (1999).
[4] E. Shaposhnikova, "Bunched beam transfer matrices in single and double rf systems", CERN SL/94-19 (RF) (1994).
[5] S. Koscielniak, “Transfer functions of hollow bunches”, TRI-DN-99-25 (1999).
[6] A. Blas, S. Hancock, S. Koscielniak, M.Lindroos, F. Pedersen, "Space-charge stabilised cold/hot spots", 9th ICFA mini-workshop, Geneva, March 2000, http://psdata.web.cern.ch/psdata/www/icfa9/
[7] S. Koscielniak, “Resonant excitation of synchrotron motion”, TRI-DN-00-09 (2000).
[8] S. Hancock, M. Lindroos, S. Koscielniak, “Longitudinal phase space tomography with space charge”, this Conf.