New Techniques for Tailoring Longitudinal Density in a Proton Synchrotron

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Abstract

The characteristics of the beam required for the Large Hadron Collider (LHC) impose stringent requirements on the CERN complex of injectors. A completely new scheme of operation, notably from the longitudinal standpoint, is foreseen for the Proton Synchrotron (PS) machine and its Booster (PSB) and has been tested in December 1993. It includes the original processes of "bunch flattening" and "bunch splitting". The first of these is applied in the PSB to reduce the space-charge induced transverse tune shift at injection in the PS. The second is employed in the PS to facilitate acceleration and debunching at high energy. Both techniques are described and the results achieved in December are presented and discussed.

1. INTRODUCTION

The PS Complex, as part of the LHC injector chain, must provide a beam whose transverse particle density exceeds, by a factor of three, the highest currently attained yet must not be diluted by more than 20% during its passage through the PS. The LHC scheme envisaged involves an upgrade of the PSB from 1 to 1.4 GeV, double-batch filling of the PS and new RF harmonics (h=1 in the PSB, h=8 in the PS) [1, 2].

The PSB routinely employs a second harmonic system to combat the space-charge induced (Laslett) tune shift from capture throughout the cycle and such a system (h=2) is foreseen in the LHC era. In addition, since beam will circulate in the PS for 1.2 s at the injection energy whilst awaiting a second batch from the PSB, an alternative technique for bunch flattening is under investigation.

Bunch splitting (from h=8 to h=16) is required at the end of the PS injection plateau to reduce the peak beam current during acceleration and to improve the adiabaticity of debunching since, in the full LHC scheme, the beam must be rebunched on h=84 before extraction to the SPS.

2. FLAT-TOPPED BUNCHES

2.1 Classical Method

Bunching factor (mean-to-peak beam current ratio) may be increased by employing second harmonic cavities to modify the potential well confining the particles within the bunch [3, 4]. Flat-topped bunches result when the second harmonic system cancels the longitudinal focusing in the bunch core.

The drawback is the need for a significant RF system which does not contribute to acceleration, although it does increase the longitudinal acceptance. Also, the beam is prone to coherent longitudinal instabilities [4] and the only practical solution found so far is to phase-lock the second harmonic system onto the beam signal itself.

2.2 Redistribution of Particles

The alternative to modifying the RF bucket is to redistribute the particles held on a single harmonic such that the line charge density of the bunch is flattened. This requires a reduction of the longitudinal phase space density at the core of the bunch. Early attempts to achieve this in the PSB were abandoned because the resultant distribution was unstable under the action of a coupled-bunch damping system. More recently, a technique has been established in the PS [5]. It is a blow-up process involving (i) a modulation, near the synchrotron frequency, of the phase between the beam and the main RF to depopulate the bunch core and (ii) some voltage applied at a much higher frequency (VHF), but slightly offset from an exact harmonic, to accelerate filamentation and smooth out the bunch shape.

Applied in the PSB shortly before extraction, the new method holds the promise of bunches which remain flat upon transfer to the PS.

2.3 PSB Experiments

Apart from the machine parameters themselves, the principal difference between the PSB tests and the development work carried out previously in the PS was the presence of a second harmonic system in the PSB. In addition, the process took place during acceleration and the ratio between VHF and main RF frequencies was lower (9 for the PSB, > 20 for the PS). The practical implementation (see Figure 1) makes extensive use of recently developed digital hardware [6], e.g., Direct Digital Synthesizers (DDS).

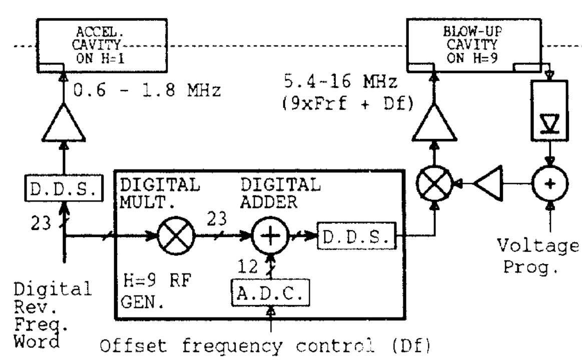
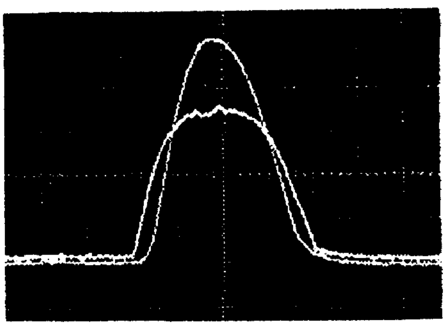


Figure 1. Layout for the production of flat-topped bunches.

The introduction of a second harmonic system radically modifies the incoherent synchrotron frequency of particles in the bunch as a function of their synchrotron amplitude. This was found to preclude the "resonant depopulation" of the bunch core which is the first part of the bunch flattening process. Indeed, the optimum phase modulation depth suggested by a simulation program treating the pure h=1 case could not be applied without drastic beam loss. Furthermore, phase modulation during acceleration was observed to drive quadrupolar bunch-shape oscillations.

Figure 2 shows the best result obtained during acceleration to 1.4 GeV, but which was not particularly reproducible. Greater bunch shape stability was achieved in a more conventional blow-up without phase modulation. Quasi-parabolic, rather than flat-topped, bunches were then readily produced and yielded the expected transverse improvements in the PS due to their increased bunching factor [7, 8].



50 ns/div.

Figure 2. Bunch profile before and after blow-up.

The longitudinal tracking program has since been adapted to include a second harmonic system. It now reproduces the observed results and highlights the importance of the phase of the second harmonic with respect to the first. The problems encountered experimentally can be attributed to the fact that the second harmonic was defocusing when the phase modulation was applied. Tracking with a focusing second harmonic, which is required before transfer to the PS, flat-topped bunches are obtained similar to those of the earlier PS experiments.

3. Bunch Splitting

3.1 Principle

Bunch splitting is an RF manipulation which divides each initial bunch into two. The harmonic number of the RF holding the beam is doubled during the process. In the case of the LHC beam in the PS, harmonics 8 and 16 are used. Figure 3 illustrates the time variation of the voltages on both harmonics, together with the transformation of the bunch contour in the longitudinal phase plane. The detected pick-up signal shows the bunch lengthening that occurs as the defocusing voltage on h=16 first begins to rise and the focusing voltage on h=8 decreases. This is followed by an increase when the bunch has been split and both halves are focused around consecutive stable phases of the h=16 voltage. Ideally the total emittance is preserved; each resultant bunch has half the emittance of the initial one. The process is the reverse of "bunch merging" used for the antiproton production beam [9].

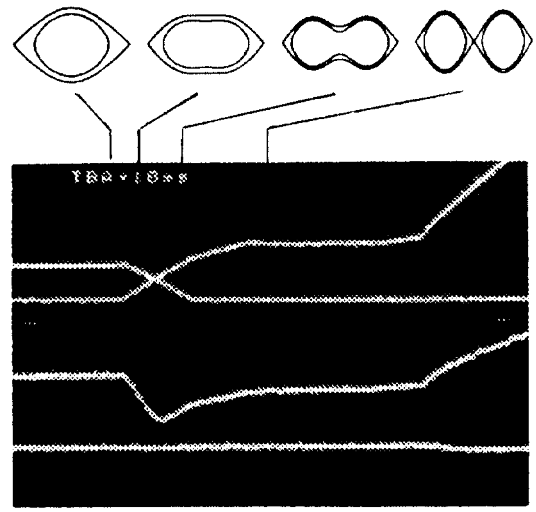


Figure 3. Evolution of the bunch splitting process at 1 GeV. Top: longitudinal phase plane. Photograph: (from top to bottom on the left) peak RF voltage on h=8, peak RF voltage on h=16, detected pick-up signal and beam current.

3.2 Implementation

The low-level RF system generates an h=16 sine wave and the h=8 is obtained after filtering the output of a divider (see Figure 4). The voltage applied to the beam on both frequencies depends upon the number of cavities on each harmonic and upon their voltage programmes.

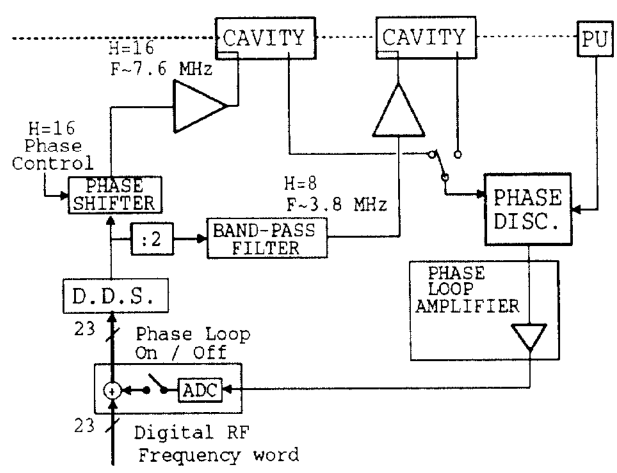


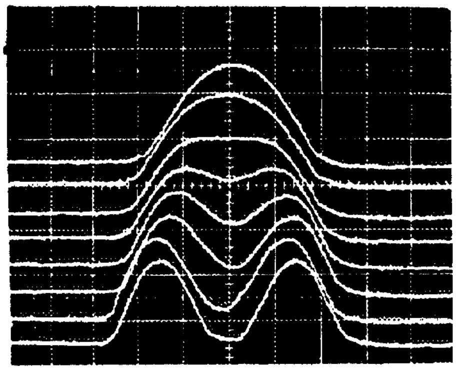
Figure 4. Hardware layout for bunch splitting.

The h=8 component of the beam current becomes negligible in the middle of the splitting process (near the minimum of the detected pick-up signal of Figure 3) and the beam phase loop has to be opened. The open-loop frequency being accurately generated [6], the beam is held until the phase loop is ready to close on the h=16 component.

A key requirement for clean splitting is to avoid disturbing the beam at these two moments. Special care is taken to reduce and increase the loop gain "slowly" and, ultimately, to disconnect and connect the ADC output to the summing node when the error signal is zero.

3.3 Results

Bunch splitting has been applied successfully at the end of the PS injection plateau, at both 1 and 1.4 GeV, with bunches of varying longitudinal emittance and shape (including parabolic, flat-topped and even triangular). Figure 5 shows a mountain range display of a longitudinal pick-up signal during a typical splitting process.



50 ns/div. 1 sweep/800 turns

Figure 5. Mountain range display of bunch splitting at 1 GeV (time increases from top to bottom).

The experience gained can be summarised as follows:

- adjustment is straightforward and no degradation due to drift is observed, at least over a period of a few days,
- there is no significant longitudinal blow-up, (< 10%),
- the process must be optimised according to the emittance, otherwise some particles leave their buckets and are lost at the beginning of acceleration (a loss of a few percent is visible in the beam current of Figure 3),
- the longitudinal distribution of particles is preserved.

4. OTHER APPLICATIONS

Both kinds of longitudinal manipulation described above have been investigated in the framework of the test of the LHC injectors and are now considered reliable tools. The capability to tailor longitudinal particle density will be extensively exploited in the PSB to optimize the operating conditions in the downstream PS. Thus, bunch splitting will also be employed in the PSB for single-batch filling of the PS at high intensity [2].

Other applications and extensions of these techniques are envisaged. For example, an improvement over the classical "adiabatic" debunching/rebunching process to change bunch spacing may be anticipated because splitting increases the threshold of longitudinal instabilities by avoiding the need to debunch the beam over the full circumference of the machine. Suitable blow-up of the longitudinal density prior to splitting should also permit bunches to be split into three.

5. REFERENCES

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