MULTIPLE BUNCH-SPLITTING IN THE PS:
RESULTS AND PLANS

R. Garoby

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1 INTRODUCTION

In the scheme originally foreseen for the preparation of the proton beam for LHC, the 25 ns bunch spacing was obtained by an iso-adiabatic debunching/rebunching at 25 GeV in the PS [1]. This method was, in simulation, just capable of delivering the required beam performance. Unfortunately, this goal proved impossible to reach in practice [2]. Another technique was then proposed to provide smaller longitudinal emittances [2,3]. Based on successive splittings of the bunches, it replaces the iso-adiabatic debunching/rebunching and automatically preserves a gap, free of particles, in the bunch train. Moreover, by changing some of the parameters, this process can deliver several different patterns of bunch train, which can be very useful for studying electron cloud induced phenomena in the downstream accelerators [4]. The first set of beam gymnastics, bunch triple-splitting, was demonstrated experimentally at the end of 1999 [5]. For the subsequent gymnastics of double splitting at 25 GeV, an adequate 20 MHz RF system was available only in 2000. All conditions were then met to test the complete process and to check whether more “exotic” bunch trains could be obtained.

2 NOMINAL BEAM FOR THE LHC

2.1 Principle

The process is shown schematically in Figure 1. Six bunches from two consecutive PSB batches, 1.2 s apart, are injected in the PS and captured in six buckets on h=7. They are first split in three at 1.4 GeV kinetic energy (injection energy), giving 18 consecutive bunches on h=21. The beam is then accelerated on this harmonic up to 25 GeV kinetic, where the bunches are twice split in two, giving a train of 72 bunches on h=84. The 12 empty buckets correspond to a particle-free gap of approximately 320 ns, to allow for the rise-time of the ejection kicker.

Figure 1: Splitting scheme for the nominal LHC beam.

In practice the following requirements have to be met:

i. to avoid bunch deformation and blow-up due to filamentation, the energy of the beam circulating in the PS at the moment of the second injection must be precisely equal to the energy of the second batch,

ii. to split the bunches into equal parts, the beam must be reproducibly stable at the beginning of each splitting step,

iii. for a robust operation, all loops controlling the beam should stay closed during the gymnastics,

iv. the beam has to be synchronized with the SPS revolution frequency before ejection at 25 GeV.

2.2 Results

A prototype 20 MHz RF system, based on a quarter-wavelength resonator filled with ferrite and equipped with a local RF feedback, has been available since the beginning of 2000. Its performance is summarized in Table 1. A high-voltage relay maintains a short-circuit across the gap until voltage is required ~20 ms before the beginning of the first splitting at 25 GeV.
Table 1: Parameters of the prototype 20 MHz RF system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Resonant frequency</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Peak voltage</td>
<td>16 kV</td>
</tr>
<tr>
<td>Q equivalent</td>
<td>~ 10</td>
</tr>
<tr>
<td>R equivalent at resonance</td>
<td>500 Ω</td>
</tr>
</tbody>
</table>

With this new system, the RF gymnastics at high energy were fully exercised. First it was implemented and adjusted with a single PSB batch of 4 bunches, and 48 nominal bunches of $1.1 \times 10^{11}$ protons were successfully ejected to the SPS. Double-batch operation was then set-up and the gymnastics was performed with 3+3=6 PSB bunches. Nominal performance has fully been achieved, with the delivery of 72 nominal bunches of $1.1 \times 10^{11}$ protons at 25 GeV. Beam losses were small and the beam was kept stable applying well-controlled longitudinal blow-ups (see Figure 2).

![Figure 2: Nominal LHC operation in the PS.](image)

Apart from some complications due to a drift of the measured B-field with respect to its real value in the dipoles, which complicated the energy adjustment at the injection of the second batch (items i. and ii. in Section 2.1), the 1.4 GeV part of the cycle was properly adjusted and proved reproducible. This was largely thanks to the beam control loops that are kept closed during the triple-splitting (item iii. in Section 2.1). The evolution of the longitudinal beam density during this process following the injection of the second PSB batch is illustrated in Figure 3.

![Figure 3: Injection of the second batch and bunch triple-splitting at 1.4 GeV; 1 $P_B = 8 \times 10^{12}$ protons.](image)

Longitudinal coupled-bunch instabilities tend to develop after transition because of higher-order mode resonances in the 40, 80 and 114 MHz cavities (at 389, 439 and 179 MHz, respectively). They are avoided using another controlled blow-up during acceleration ~100 ms after crossing transition. At this stage, the bunch emittance is ~1.1 eVs, less than that of 4 nominal bunches after quadruple-splitting ($4 \times 0.35=1.4$ eVs) and thus within LHC requirements.

On the 25 GeV flat top, the beam revolution frequency has to be synchronized to a reference derived from the SPS trains (item iv. in Section 2.1). Preserving this synchronization while the voltage on $h=21$ is reduced to 10 kV (initial condition before the first splitting in two), necessitates a precise adjustment of the relative phase between the cavities which are successively turned off in groups to achieve the voltage reduction (see Figure 4).

Phase-modulated RF at ~200 MHz is applied before triple splitting to smooth the shape of the bunches and to increase their emittance. This compensates for the imperfect longitudinal matching of the second batch and for the insufficient longitudinal emittance of the PSB bunches.

![Figure 4: Voltage programmes of the ferrite cavities at the beginning of the 25 GeV flat top.](image)
The first double splitting at 25 GeV starts 2260 ms into the cycle, when the voltage on h=42 (20 MHz) begins to increase. At the same time, the RF drive of the cavities on h=21 (C56 and 66) is switched onto a signal derived from the SPS trains, so that the beam control loops become ineffective and the subsequent gymnastics are carried out with fixed RF drives. The consequence is that beam phase oscillations are not damped anymore and the quality of the gymnastics is strongly dependent upon the reproducibility of the initial conditions (see Figure 5). This is a source of some inequality between bunches after the two double-splittings, as visible in Figure 6.

Figure 5: Quadruple splitting at 25 GeV; \( I_p = 8 \times 10^{12} \) protons.
[Vertical scale: 1 trace/1250 revolutions (2.6 ms).]

Figure 6: Bunch train before ejection at 25 GeV; \( N_b = 1.1 \times 10^11 \) protons/bunch/20%.

The bunches are rotated in the longitudinal phase plane by increasing rapidly the voltage on h=84 (40 MHz) from 100 to 300 kV and by turning on the h=168 cavities in less than 20 μs. They are ejected when they are shortest. Figure 7 shows that the 4 ns nominal bunch length has been comfortably met. However, there is a ±0.2 ns variation from bunch to bunch.

Figure 7: Bunch at ejection to the SPS; \( N_b = 1.1 \times 10^{11} \) protons.

2.3 Comments

The experimental results demonstrate the capability of the new scheme based on multiple splittings to provide beam with the basic longitudinal characteristics required for the LHC. However, the equality between bunches has to be improved by at least a factor of two (goal: ±10%) and performance stability has to be enhanced. The following issues have been identified as the main factors needing further work:

- The beams from the all PSB rings have to meet reproducibly the nominal characteristics.
- The accuracy of the PS B-field measurement system must be improved.
- Servo-loops must be implemented in the PS beam control to stabilize performance.
- Coupled-bunch instabilities must be fought in the PS by reducing the impedance of the offending resonances and, possibly, by installing a damping system.

3 ALTERNATIVE BUNCH TRAINS

3.1 50 ns bunch spacing

A train of bunches spaced by 50 ns is obtained using the process previously described at 1.4 GeV (see Figure 1), but with only the first of the two splittings in two at 25 GeV [4]. The RF is, in fact, the same as if the last splitting were taking place, but with the opposite phase on h=84, so that the bunches are compressed instead of being split.

During acceleration on h=21, the bunches must have half the intensity and half the emittance than for the nominal beam. This could not be achieved because of longitudinal coupled-bunch instabilities above transition. Figure 8 shows the observed perturbation of a peak-detected pick-up signal and of the modulation of the
pick-up signal around $h=20$ (coupled-bunch modes $n=1$ and 20) when the longitudinal emittance is not blown-up sufficiently. This underlines the importance of the actions planned to combat the higher-order mode resonances of the various RF systems (see Section 2.3).

Figure 8: Longitudinal instabilities during acceleration with two 80 MHz and one 40 MHz cavity gaps open; $I_p = 5 \times 10^{12}$ protons from 7 PSB bunches.
[Traces from bottom to top: HOM on 80 MHz cavity, peak pick-up signal, demodulated signal around $h=20$.]

Figure 9: Double splitting at 25 GeV; $I_p = 2.1 \times 10^{12}$ protons from 6 PSB bunches.
[Vertical scale: 1 trace/ 1300 revolutions (2.7 ms).]

Quasi-nominal emittances at ejection could only be obtained at half the intensity per bunch ($N_b \sim 0.6 \times 10^{11}$). The mountain range display in Figure 9 illustrates the operation at 25 GeV under these conditions.

3.2 25 ns bunch spacing and 120 ns gaps

By splitting bunches into two $h=21$ buckets instead of into three at 1.4 GeV, a ~120 ns gap is generated and is preserved until ejection (see Figure 10 w.r.t. Figure 1).

This procedure was successfully tested and nominal bunches ($0.35$ eVs, $1.1 \times 10^{11}$ protons/bunch) were obtained. The gymnastics at 1.4 and 25 GeV are shown in Figures 11 and 12, respectively (cf. Figures 3 and 5).

4 PLANS

4.1 75 ns bunch spacing

If electron-cloud-induced heating [6] is too severe with 25 ns spaced bunches in the initial phase of LHC operation, then bunch trains with 75 ns spacing could be very useful to reduce drastically the electron cloud problem while providing one third of the luminosity in all interaction points. To generate such a train, a scheme based on two double splittings in the PS is proposed (see Figure 13). In addition to some new low-level electronics, an RF system delivering up to 15 kV at
13.3 MHz is foreseen. Since the final 20 MHz RF system for the nominal splitting on \( h=42 \) still has to be built, the proposal is to make it tunable and hence capable of operating at 13.3 MHz as well.

**Figure 12:** Quadruple splitting at 25 GeV; 1.3 × 10^13 protons from 6 PSB bunches. [Vertical scale: 1 trace/1250 revolutions (2.6 ms).]

**Figure 13:** Splitting scheme for 75 ns bunch spacing.

### 4.2 Actions

The actions planned to improve and stabilize the performance of the beams already obtained, and to prepare for the new type of bunch train, are listed in Table 2. Most of them should provide noticeable improvements already in 2001. However, it is estimated that the design and construction of an operational RF system, capable of both 13.3 and 20 MHz, will take two years, provided the necessary budget is made available.

<table>
<thead>
<tr>
<th>Item</th>
<th>Action</th>
<th>Deadline</th>
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<tbody>
<tr>
<td>PSB long. beam char.</td>
<td>Optimize long. controlled blow-up</td>
<td>09/2001</td>
</tr>
<tr>
<td></td>
<td>Upgrade synchronization</td>
<td></td>
</tr>
<tr>
<td>Phasing of ferrite cavities</td>
<td>Optimize tuning range for proper operation at 10 MHz</td>
<td>03/2001</td>
</tr>
<tr>
<td></td>
<td>Servo-system?</td>
<td>to be defined</td>
</tr>
<tr>
<td>B measur.</td>
<td>Implement and test new B-train equipment</td>
<td>06/2001</td>
</tr>
<tr>
<td>Coupled bunch instab.</td>
<td>Remove 114 MHz cavities</td>
<td>03/2001</td>
</tr>
<tr>
<td></td>
<td>Improve HOM dampers in 80 MHz cavities</td>
<td>06/2001</td>
</tr>
<tr>
<td></td>
<td>Active beam instability damping (2 modes)</td>
<td>09/2001</td>
</tr>
<tr>
<td>Reliability and 75 ns spacing</td>
<td>Build full performance RF system for the PS [2×15 kV @ 13.3 or 20 MHz]</td>
<td>03/2003</td>
</tr>
</tbody>
</table>

### 5 CONCLUSIONS

The proof has been made that the multiple splitting process enables the PS to deliver the nominal proton beam for the LHC and to provide a variety of different bunch trains.

Efforts must now be focused on equalizing the longitudinal characteristics of bunches inside each PS pulse and between such pulses.

### ACKNOWLEDGEMENTS

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### REFERENCES