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STATUS OF THE NOMINAL PROTON BEAM FOR LHC IN THE PS

R. Garoby

Abstract

The RF systems which are necessary for the generation of the nominal proton beam for the LHC in the PS Complex have been installed in the PSB and in the PS during the shutdown 97-98. This has permitted the complete set of longitudinal operations required by this beam to be tested and adjusted. The hardware status and the results achieved so far are summarised in this paper. The subjects of study, the foreseen improvements and the expected beam characteristics in 1999 are also described.

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The RF systems which are necessary for the generation of the nominal proton beam for the LHC in the PS Complex have been installed in the PSB and in the PS during the shutdown 97-98. This has permitted the complete set of longitudinal operations required by this beam to be tested and adjusted. The hardware status and the results achieved so far are summarised in this paper. The subjects of study, the foreseen improvements and the expected beam characteristics in 1999 are also described.

1 HARDWARE STATUS

New hardware is needed and numerous modifications must be made to prepare the accelerators of the PS Complex for their future role as LHC injectors [1]. The two major developments concern the increase of the PSB-to-PS transfer energy to 1.4 GeV and a complete change of the longitudinal beam operations and hence of the RF systems. The installation of the required RF equipment [2] was largely achieved during the shutdown 97-98, while the increase of transfer energy will only be treated in 1999.

The characteristics of the three RF systems now active in each PSB ring are summarised in Table 1.

Table 1: Parameters of the PSB RF systems.
[S.C.: short-circuit relay.]

Name	**Freq. (MHz)**	**Vpeak per cavity (kV)**	**HF feedback gain (dB)**	**Impedance per cavity (Ω)**
C02	0.6 – 1.8	8	20	300
C04	1.2 – 3.9	8	20 - 26	900 (+ S.C.)
C16	6 - 17	6	13 - 26	1500 (+ S.C.)

The C02 equipment is a new development [3] which performed very reliably during 1998, except for a high voltage breakdown in one of the cavities after a test at an excessive power level. The C04 systems stem from a modification of the old C08 one [3], which previously served for acceleration on harmonic 5. The C16 cavities are unchanged. The beam controls driving these cavities have all been rebuilt to cover the necessary frequency range and harmonic numbers. They now permit new gymnastics like "bunch splitting" and "controlled longitudinal blow-up".

In the PS, three new RF systems have been installed, one operating at 40 MHz [4] and two at 80 MHz [5]. The RF equipment now available is summarised in Table 2.

Table 2: Parameters of the PS RF systems.
[S.C.: relay or mechanical short-circuit.]

Name (nb. of cav.)	**Freq. (MHz)**	**Vpeak per cavity (kV)**	**HF feedback gain (dB)**	**Impedance per cavity (kΩ)**
C10 (11)	2.7 – 9.6	20	20	0.7 (+ S.C.)
C40 (1)	40.050	300	43	2.4 (+ S.C.)
C80 (2)	80.100	300	44	5.7 (+ S.C.)
C200 (8)	199.950	30	-	7 (+ damping)
C114 (2)	114.511	500	-	3000 (+ S.C.)

2 PERFORMANCE

2.1 Beams for physics

The first priority after the winter shutdown was to achieve a similar or better performance than that of 1997 for the physics experiments [6]. That goal was met successively for all scheduled beams and record numbers of protons and ions were delivered onto targets. Experience has confirmed the efficiency and reliability – even at the highest beam intensities – of the bunch splitting process, which is now in operational use both in the PSB and in the PS (figure 1).

2.2 LHC-type beam

The status of advancement of the various stages of the process by which the proton beam for LHC is generated is outlined in Table 3.

As far as longitudinal beam parameters are concerned, the PSB is fully ready and has demonstrated its ability to deliver bunches with adequate characteristics. Only the transverse beam parameters are expected to benefit from the increased transfer energy of 1.4 GeV and from the double batch transfers which will be tried out in 1999.

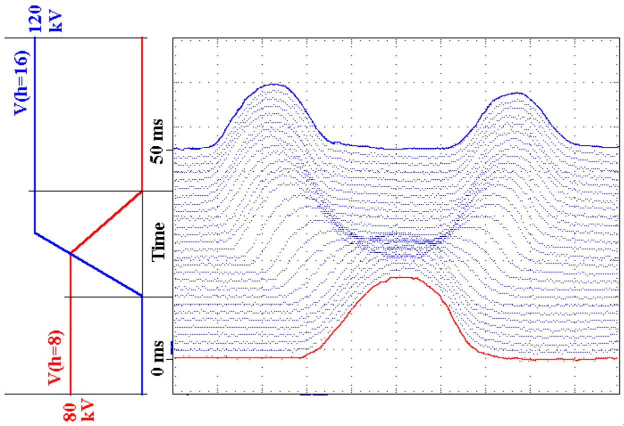

Figure 1: Beam pick-up signal and RF voltages during splitting at 3.57 GeV/c in the PS.

In the PS, all the longitudinal beam gymnastics have been put into operation and beams of 1×10^{10} up to 1×10^{11} protons per bunch have been delivered to the SPS during MD periods.

Table 3: Status of beam preparation for LHC.

Machine	Process stage	Status in 1998
PSB	– Capture & accel. of 1 bunch per ring (h=1+2) – Controlled long. blow-up (h=9) – Double batch transfer to the PS – $T_{TRANSFER}$= 1.4 GeV	– OK but used with splitting at 1 GeV – Fully operational – Available but not used – 1 GeV only
PS	– Capture & accel. on h=8 up to 3.57 GeV/c – Splitting & blow-up at 3.57 GeV/c – Accel. on h=16 up to 26 GeV/c – Adiabatic debunching (h=16) & rebunching (h=84) – Bunch rotation	– Fully operational – Fully operational – Fully operational – Working – Working

Figure 2 shows the evolution of the peak line density (detected pick-up) during a complete machine cycle. Figure 3 illustrates, at 50 µs/div, some details of the bunch rotation process which takes place before ejection. The rise-time of the voltage on the 40 and 80 MHz cavities meets the specifications (< 20 µs) and triggers small phase perturbations (< 5 deg).

The following improvements have been obtained with respect to 1997 [7]:

- acceleration up to 26 GeV/c and debunching now take place on the nominal harmonics (h=16),
- no spontaneous rebunching is observed on the debunched beam, which proves that the large resonance due to a bad contact of a short-circuit arm in a 114 MHz cavity is now cured,
- rebunching and bunch rotation take place while the ejection bump is pulsing without visible degradation of the bunch shape thanks to compensation of the increase in orbit length by the cavity phase programme.

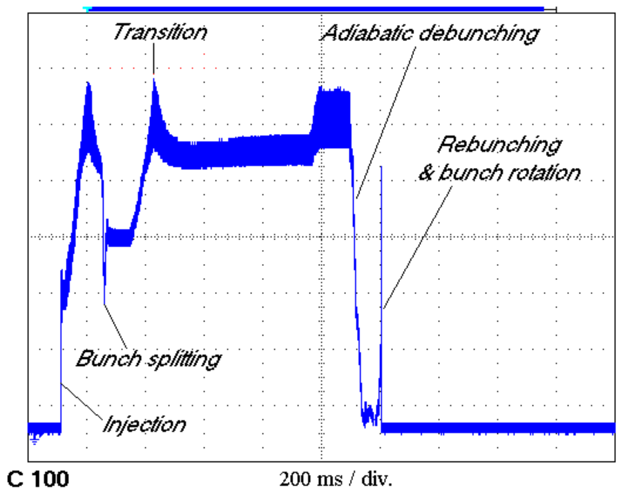

Figure 2: Peak beam pick-up signal during an LHC-type cycle in the PS.

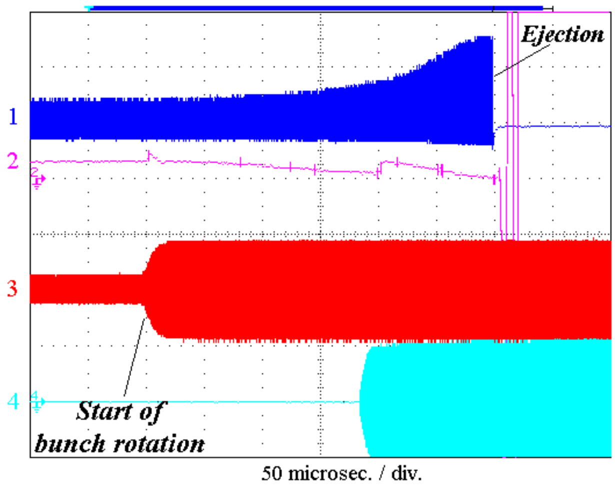

Figure 3: Bunch rotation before ejection with 9×10^{12} protons (~ nominal intensity).
[1: Beam pick-up; 2: Beam/cavity phase at 40 MHz (10 deg/div); 3: 40 MHz voltage; 4: 80 MHz voltage.]

Although the RF hardware works as specified, experiments have confirmed the anticipated difficulty in meeting the tight budget for longitudinal emittance during the debunching-rebunching process [8]. In practice, the emittance is deliberately blown up at 3.57 GeV/c until no instability is visible during the remainder of the cycle and especially after debunching. Figure 4 shows the Schottky spectrum of a beam of nominal intensity during the 26 GeV/c flat-top. A very slight instability can be observed. After rebunching and bunch rotation, the resultant bunch is then approximately 5 ns long instead of the desired 4 ns (figure 5).

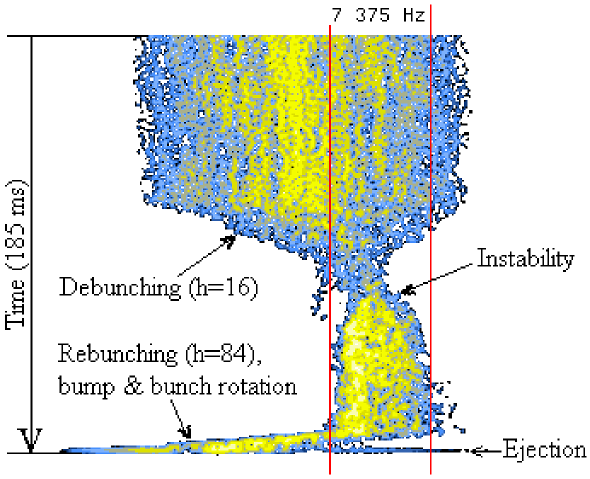

Figure 4: Longitudinal Schottky spectrum at 26 GeV/c with 9×10^{12} protons (~ nominal intensity). [Centre freq.: 395 MHz, freq. span: 50 kHz.]

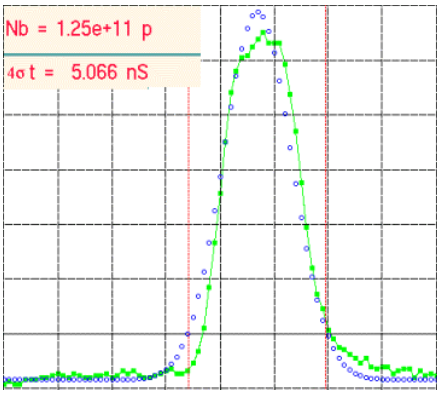

Figure 5: Bunch at ejection (~ nominal intensity). [σ_T : rms width of gaussian fit.]

At lower intensity, the longitudinal emittance can be kept smaller and bunch length decreases accordingly (figures 6 and 7).

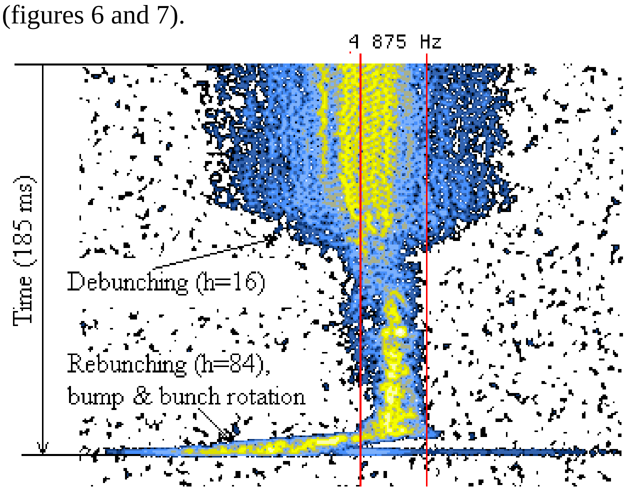

Figure 6: Longitudinal Schottky spectrum at 26 GeV/c with 1×10^{12} protons (~ nominal intensity/10). [Centre freq.: 395 MHz, freq. span: 50 kHz.]

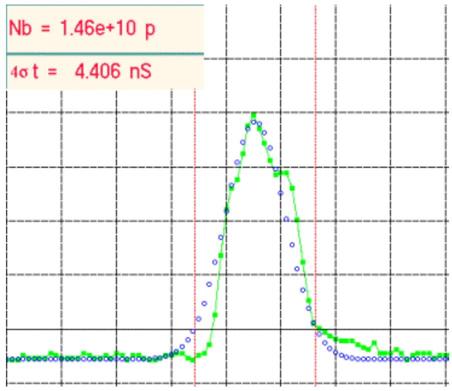

Figure 7: Bunch at ejection (~ nominal intensity/10). [σ_T : rms width of gaussian fit.]

As summarised in Table 4, the longitudinal beam characteristics obtained in 1998 do not meet the specifications of the LHC proton beam for the SPS. Estimated limits of uncertainty are given for the bunch length and bunch emittance at ejection.

Table 4: Longitudinal characteristics of the proton beam for LHC in the PS in 1998.

Intensity (protons / bunch)	1×10^{10} (1998)	1×10^{11} (1998)	**1×10^{11} nominal**
ε_l per bunch before debunching (eVs)	0.9	1.2	**1**
ε_l per bunch at ejection (eVs)	0.4 ± 0.05	0.5 ± 0.05	**0.35**
Bunch length at ejection (ns)	4.3 ± 0.2	5 ± 0.2	**4**
Total Δp/p at ejection	4.3×10^{-3}	4.5×10^{-3}	**4.1×10^{-3}**

3 IMPROVEMENT PLAN

3.1 Reduction of the longitudinal emittance

Given the successful operational experience with bunch splitting, it is proposed [9] to use it to avoid debunching + rebunching. This has the following advantages:

- preserve a gap without beam for the rise-time of the ejection kicker,
- minimise emittance blow-up due to RF hardware limitations,
- improve stability by staying further from the microwave instability threshold,
- improve reproducibility by always keeping the beam under the control of a beam phase loop.

The principle of the process is sketched in figure 8. The PS captures bunches on harmonic 7 (instead of 8 in the reference design), which implies that only 7 PSB rings will be necessary to completely fill the PS and, consequently, that the intensity per ring needs to increase by 15%. The beam is accelerated on that harmonic up to 3.57 GeV/c, where each bunch is split into three by applying the appropriate amplitude and phase parameters to 3 groups of cavities operating on harmonics 7, 14 and 21, respectively. These harmonics should be within the capabilities of the existing ferrite cavity systems in the PS. Simulation results indicate that this process has the potential to preserve longitudinal emittance (figure 9).

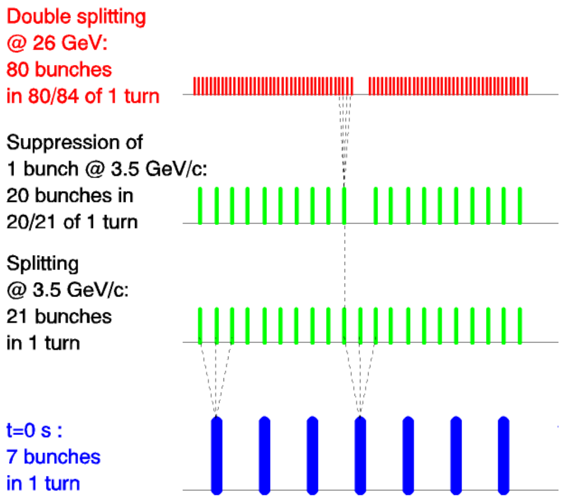

Figure 8: Generation of an LHC-type beam in the PS without debunching + rebunching.

One bunch is then eliminated by fast ejection to a dump target. This requires improvements to the PS ejection and beam transfer system. Twenty bunches are left and are accelerated up to 26 GeV/c on h=21. Each bunch is then split twice into two using the process which has already been demonstrated in regular operation. A new 20 MHz, 20 kV RF system is required at that stage. Finally, the PS circumference is filled with a train of 80 bunches on h=84 followed by a gap of 4 bunches (120 ns) which matches the ejection kicker rise-time. Simulation results are shown in figure 10.

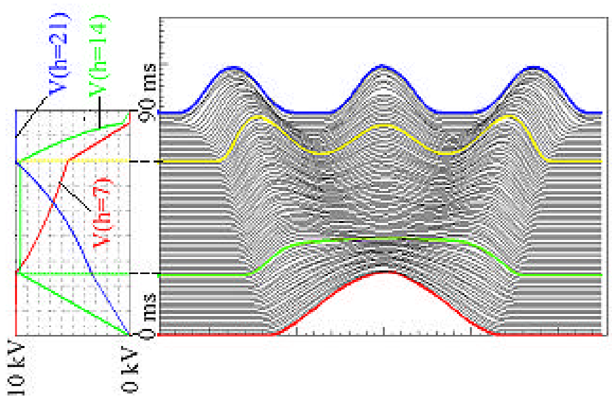

Figure 9: Splitting bunches into three at 3.57 GeV/c in the PS (ESME simulation).

Experiments will be performed in the PS in 1999 to demonstrate the feasibility of splitting bunches into three. A prototype 20 MHz system is under development and will be installed in the machine during the shutdown 1999-2000. If successful, the planned cascade of splitting should permit the delivery of the low emittance bunches required by the LHC in 2000.

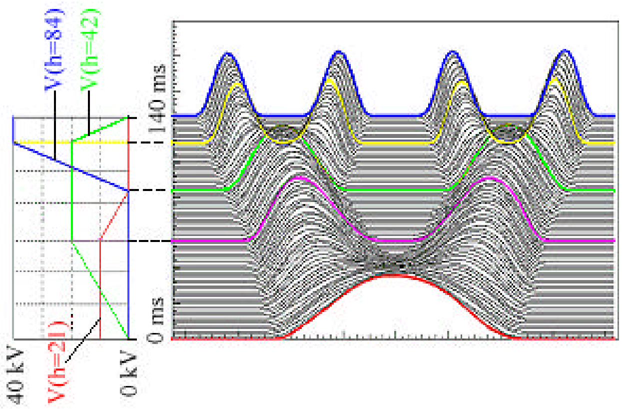

Figure 10: Splitting bunches into four at 26 GeV/c in the PS (ESME simulation).

It would be easier for the PS to suppress one of the bunches at injection from the PSB on h=7. But the beam transferred to the SPS would then consist of only 72 bunches and no satisfactory LHC filling scheme has yet been devised which would then provide the luminosity anticipated by the experiments and satisfy all symmetry requirements.

3.2 Reduction of the bunch length

During the shutdown 98-99, spare cavities (one 40 MHz and one 80 MHz) will be installed in the PS ring. Using them in conjunction with the others, the total voltage available can be increased and bunch length can be reduced at the cost of increasing the energy spread. This is summarised in Table 5 (note that the newly installed 40 MHz cavity has a different coupling between amplifier and cavity and provides up to 450 kV instead of 300 kV).

Table 5: Bunch length and total Δp/p at ejection as a function of the RF voltages.

	300 kV @ 40 MHz (Cav. 98)	**450 kV @ 40 MHz (Cav. 99)**	**750 kV @ 40 MHz (Cav. 98 + Cav. 99)**
600 kV @ 80 MHz (2 cavities)	5ns 4.5×10^{-3}	4.8 ns 4.6×10^{-3}	4.4 ns 5.2×10^{-3}
900 kV @ 80 MHz (3 cavities)	4.4 ns 5×10^{-3}	4.3 ns 5.2×10^{-3}	3.9 ns 5.7×10^{-3}

4 CONCLUSION

Important milestones have been met in 1998 with regard to the preparation of the PS Complex for the LHC:

- the RF equipment required to operate the PSB and the PS during the LHC era has been installed and has met its specifications,
- the new modes of operation scheduled for physics have been successfully employed and record performances have been achieved,
- trials have been conducted to generate the proton beam for the LHC and the longitudinal emittance of the bunches is 40% too large at the nominal intensity (1×10^{11} ppb).

The following actions are being undertaken to improve the situation and ultimately to reach the specified level of performance:

- using the spare 40 and 80 MHz systems being installed during the shutdown 98-99 shorter bunches can already be generated in 1999, although still with an excessive emittance,
- attempts will be made in the years 1999 and 2000 to generalize splitting and avoid debunching + rebunching, providing the potential to reach the proper emittance and keep a gap for the ejection kicker,
- removal of the 114 MHz cavities from the PS ring after the end of LEP (in 2001) will help decrease the PS impedance and improve beam stability.

ACKNOWLEDGEMENTS

The impressive results achieved in 1998 are due to the collective effort of many individuals. Based on the clever design and hard work of a number of specialists in the PS-RF group, it could only have been a success with the support of control room colleagues and of numerous contributors from the other divisions at CERN and also from TRIUMF.

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