CHAPTER 7

BUNCH SPLITTING AND BUNCH ROTATION IN THE PS

7.1 NOMINAL BUNCH TRAIN SCHEME

In the nominal mode of operation for filling LHC, the PS delivers beam every 3.6 s in batches of 72 bunches spaced by 25 ns. This interval between bunches is preserved up to the LHC. To prepare this beam from the 6 bunches supplied by the PSB in two batches, specially developed splitting schemes are used [1].

Moreover, for a proper capture by the 200 MHz RF in the SPS, a bunch rotation process is applied just before ejection from the PS to reduce the 0.35 eVs bunches to 4 ns length.

Many different LHC filling schemes can be applied [2], the most favourable ones requiring the SPS to capture and accelerate 4 batches of 72 bunches from the PS.

7.1.1 Bunch Splittings

The complete process is sketched in Fig. 7.1. Six bunches delivered in two batches by the PSB are captured on harmonic $h = 7$ in the PS. Triple splitting is started as soon as the second batch is received, which provides 18 consecutive bunches on $h = 21$. The beam is then accelerated on this harmonic up to the 25 GeV flat-top, where each bunch is twice split in two to give 72 consecutive bunches on $h = 84$. This leaves a 320 ns gap in the bunch train for the rise-time of the ejection kicker.

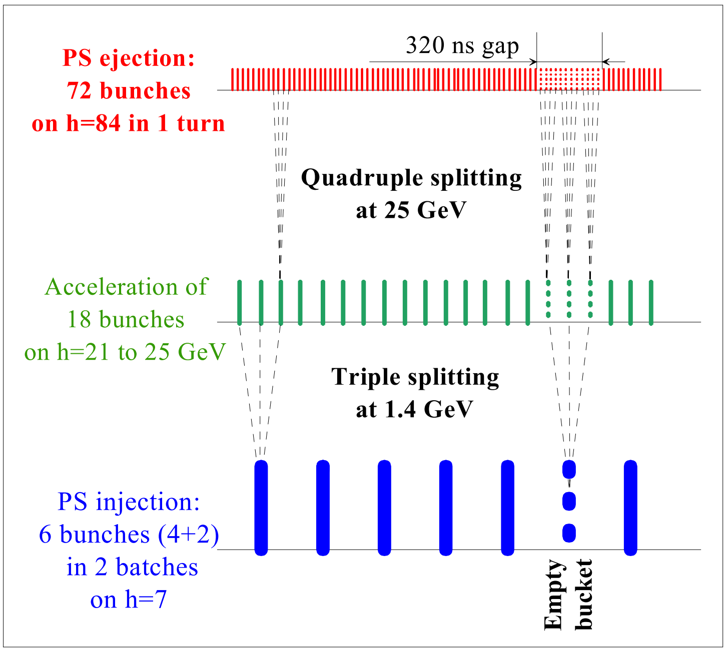

Figure 7.1: Generation of the nominal bunch train for LHC (25 ns bunch spacing).

Triple splitting requires three simultaneous RF harmonics ($h = 7$, 14 and 21). The voltages of these three components and the corresponding evolution of the distribution of particles in the longitudinal phase plane are represented in Fig. 7.2. A stable phase on $h = 21$ and an unstable phase on $h = 14$ coincide with the stable phase on $h = 7$. Starting with $h = 7$ alone, the effect of increasing the voltages on $h = 14$ and 21 is to flatten the bunch (t=7 ms in Fig. 7.2). In phase space, two new stable points emerge close to the initial one, encircled by 3 buckets. If the rate of change of the voltages is sufficiently slow, the particles of the initial bunch are gradually captured in these new buckets, whose area grows as the voltage decreases on $h = 7$ and increases on $h = 21$ (t=14 ms in Fig. 7.2). Using numerically determined laws of variation, the three areas are kept equal throughout the process, so that layers of increasing emittance in the initial bunch are progressively peeled off and accumulated evenly into the three new buckets. Three equal bunches are finally obtained, each with the same distribution of particle density as the initial one (t=25 ms in Fig. 7.2). A beam phase loop is active during the whole process (see Sec. 7.4). It controls the phase of the sum of all harmonics, whose relative phase is rigidly fixed. Avoiding collective beam oscillations with respect to the RF is essential to preserve the total longitudinal emittance and obtain equal bunches (Fig. 7.3).

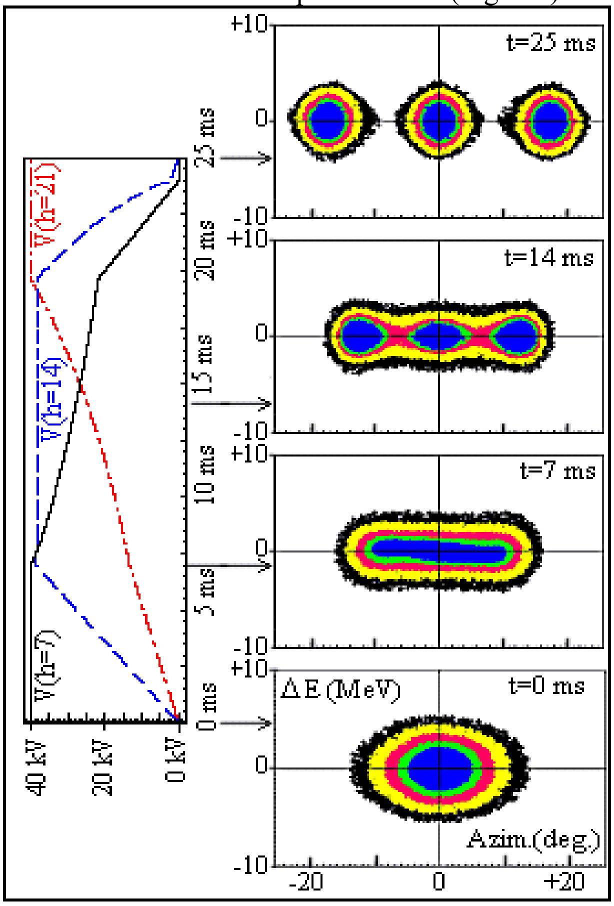

Figure 7.2: Simulation of triple splitting at 1.4 GeV in the PS.

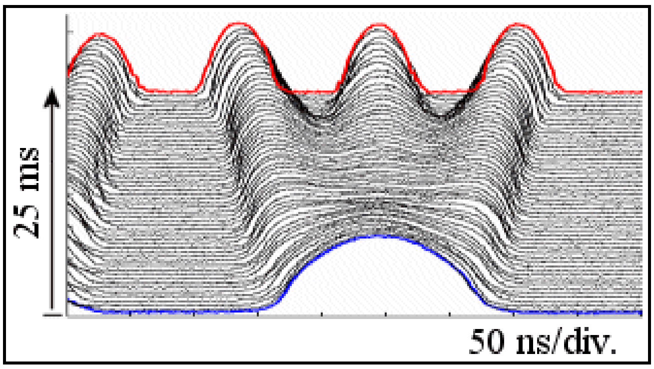

Figure 7.3: Triple splitting for the nominal beam (initial PSB bunch ~ 1.35 × 10^{12} protons).

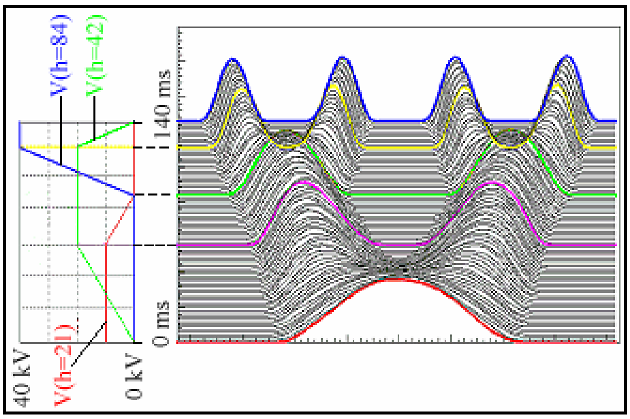

Figure 7.4: Quadruple splitting in the PS (ESME simulation).

For quadruple splitting at 25 GeV three groups of cavities, also operating on harmonics 21, 42 and 84 are employed. New 20 and 40 MHz RF systems have been installed in the PS for these last two harmonics (see Chap. 8). This scheme is a duplication of the splitting in two process which is extensively used in regular operation. The relative phase between harmonics is rigidly fixed and a beam phase loop suppresses collective oscillations with respect to the RF sum voltage. Simulation (Fig. 7.4) predicts that the longitudinal emittance will not increase and this is also approximately observed in reality (Fig. 7.5). Performance degrades as intensity increases, because of coupled bunch instabilities which give different initial conditions for the different bunches and lead to discrepancies between the bunches.

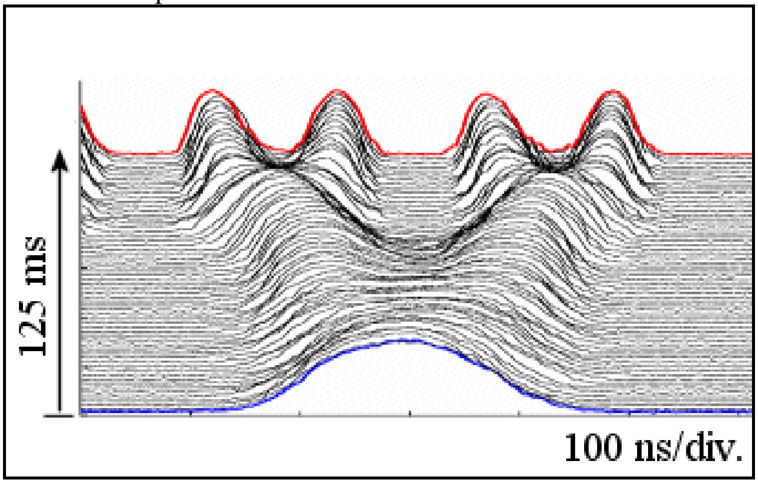

Figure 7.5: Splitting of a bunch of ~ 0.45×10^{12} protons at 25 GeV in the PS.

The parameters of the overall process are summarised in Tab. 7.1 (the intensities quoted assume 100% transmission from PSB to the LHC). The only disadvantage with the nominal bunch train scheme is that, since it uses only 7/8 of the total PSB intensity, the intensity per ring and the beam brightness in that machine have to be 14% higher than for the original scheme [3]. As a consequence, the PSB can no longer achieve the brightness and intensity required for the ultimate beam in the LHC (see Sec. 2.3 and 10.5). This is however counter-balanced by the fact that the beam is always under control of the RF, so that phase oscillation damping loops can be active and the necessary performance can be reliably attained. In addition there are the following features:

- The beam is never debunched, so that the microwave instability threshold is less of a concern.
- The gap without particles corresponding to the missing PSB bunch is preserved. This empty gap of 320 ns at ejection gives ample space for the rise-time of the kicker.

Table 7.1: Nominal PS complex operation for filling LHC.

No. of bunches per PSB ring	1
No. of PSB cycles per PS cycle	2
No. of bunches from PSB per PS cycle	6
h at PS injection	7
Bunch splitting at 1.4 GeV	1=>3
h between 1.4 and 25 GeV	21
No. of bunches between 1.4 and 25 GeV	18
Gymnastics at 25 GeV	Double bunch splitting (1=>4)
h at PS extraction	84
No. of bunches to SPS per PS cycle	72
PS intensity at 1.4 GeV for $1.15 \cdot 10^{11}$ p/LHC bunch (nominal)	8.28×10^{12}
Intensity per PSB ring	1.38×10^{12}

7.1.2 Bunch Rotation

At the end of the splitting process at 25 GeV, each of the 72 bunches, held by 100 kV of RF on h = 84 (40 MHz), is 11 ns long. The following non-adiabatic procedure is then applied to reduce it to 4 ns:

- 290 µs before ejection, the voltage on h = 84 is stepped up to 300 kV in approximately 20 µs,
- 180 µs later, the voltage on h = 168 (80 MHz) is stepped up to 300 kV in approximately 20 µs.
- 110 µs later, ejection is triggered when the bunches are at their shortest.

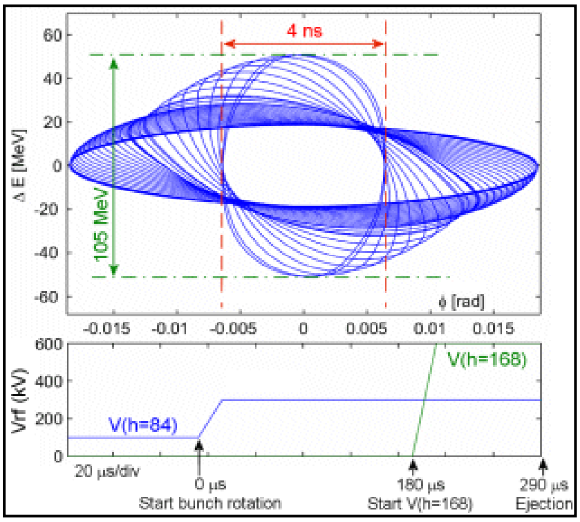

Figure 7.6: RF voltages (bottom) and bunch contour (top) during bunch rotation at 25 GeV.

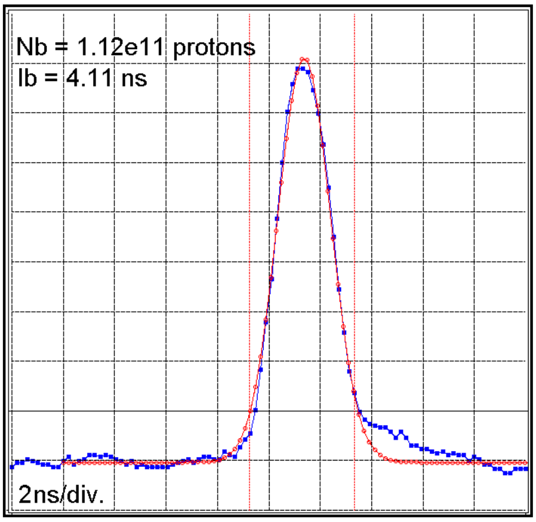

Figure 7.7: Nominal bunch at ejection to the SPS.

This is illustrated in Fig. 7.6, together with the computed result in the longitudinal phase space. No distortion is visible on the final contour. The experimental result measured with a nominal intensity beam is shown in Fig. 7.7.

7.2 ALTERNATIVE BUNCH TRAINS

Electron multipactoring (manifesting itself as the electron cloud effect) has recently been diagnosed as a dominant contributor to the heat load to the LHC cryogenic system, potentially limiting drastically the machine performance [4]. Among the many actions envisaged to solve the problem, a number of them require the beam time structure to be modified, either doubling the distance between bunches or introducing more gaps in the bunch train.

The multiple splitting technique is extremely flexible and offers several possibilities of changing the bunch train in ways which could not be achieved using the initial, more conventional debunching-rebunching technique.

7.2.1 75 ns Bunch Spacing

Keeping the same intensity per bunch, but changing the separation between bunches from 25 to 75 ns, the electron cloud problem can be drastically reduced, both in the SPS and in the LHC, while providing one third of the luminosity in all interaction points of the collider. To generate such a train, a scheme based on two double splittings in the PS is being used (Fig. 7.8).

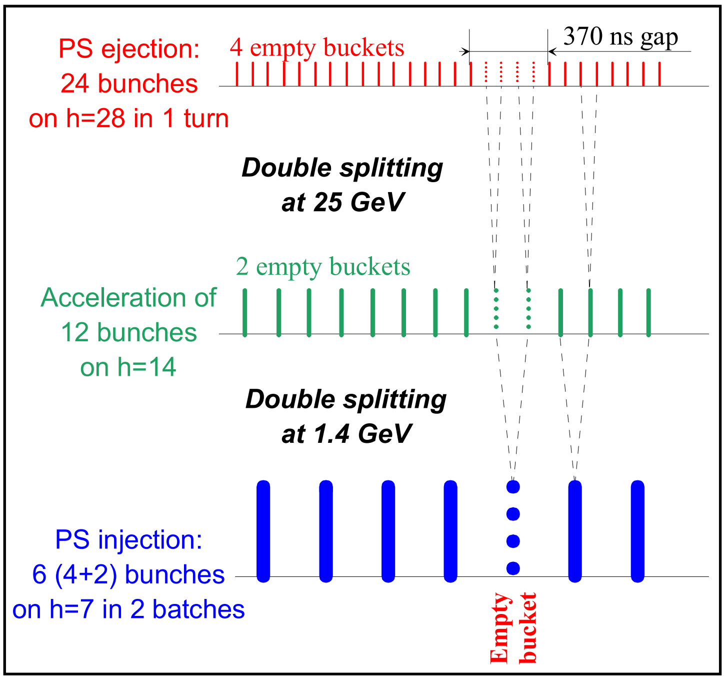

Figure 7.8: Generation of a 75 ns bunch train.

Six bunches delivered in two batches by the PSB are captured on harmonic $h = 7$ in the PS. Double splitting is started as soon as the second batch is received, which provides 12 consecutive bunches on $h = 14$. The beam is then accelerated on this harmonic up to the 25 GeV flat-top, where each bunch is again split in two to give 24 consecutive bunches on $h = 28$. They are then captured on $h = 84$ without any further splitting and the bunch rotation process is triggered with the same initial conditions as in the nominal scheme. This leaves a 370 ns gap in the bunch train for the rise-time of the ejection kicker. The 15 kV necessary on $h = 28$ (13.3 MHz) are delivered by the new RF system which was prepared for operation on $h = 42$ (20 MHz) but which has been made tuneable (Sec. 8.1).

Typical results when delivering the nominal intensity per bunch are shown in Fig. 7.9 and Fig. 7.10.

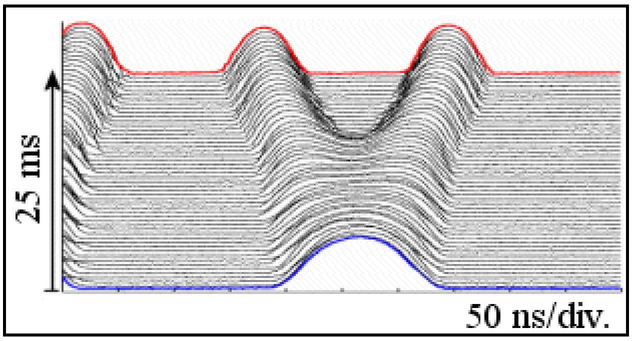

Figure 7.9: Splitting from h = 7 to h = 14 of a bunch of ~ 5×10^{11} protons at 1.4 GeV in the PS.

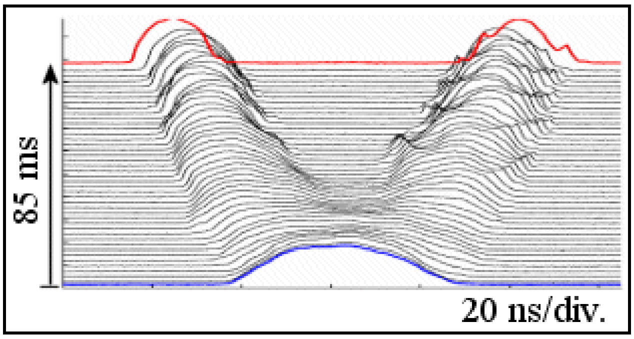

Figure 7.10: Splitting from h = 14 to h = 28 of a bunch of 2.3×10^{11} protons at 25 GeV in the PS.

7.2.2 50 ns Bunch Spacing

Bringing the separation between bunches from 25 to 50 ns, with the same intensity per bunch, the electron cloud problem will also be reduced, although by a smaller factor than with 75 ns spacing. Luminosity in the LHC, will reach one half of the nominal value, but not simultaneously in all three interaction regions. Such a train is obtained with the process described in Sec. 7.1.1 for the nominal beam, but without the second splitting in two at 25 GeV. The RF on $h = 84$ is turned on with opposite phase, so that the bunches are more focused by the action of this harmonic instead of being split. A total of 36 bunches are finally obtained, spaced by 50 ns and with a 345 ns gap without particles. Proper operation of this scheme has been demonstrated at the nominal intensity per LHC bunch.

7.2.3 Exotic Bunch Trains

In all the previously described bunch trains, it is operationally simple to create more gaps without beam by suppressing one or more PSB bunches.

Moreover, if necessary, other types of beams can be prepared, for example by changing the phasing between harmonics 7, 14 and 21 at 1.4 GeV (Fig. 7.11) to split bunches in two instead of three. This gives 8 bursts of 7 bunches spaced by 25 ns, separated by 4 empty buckets (120 ns gaps) at 25 GeV.

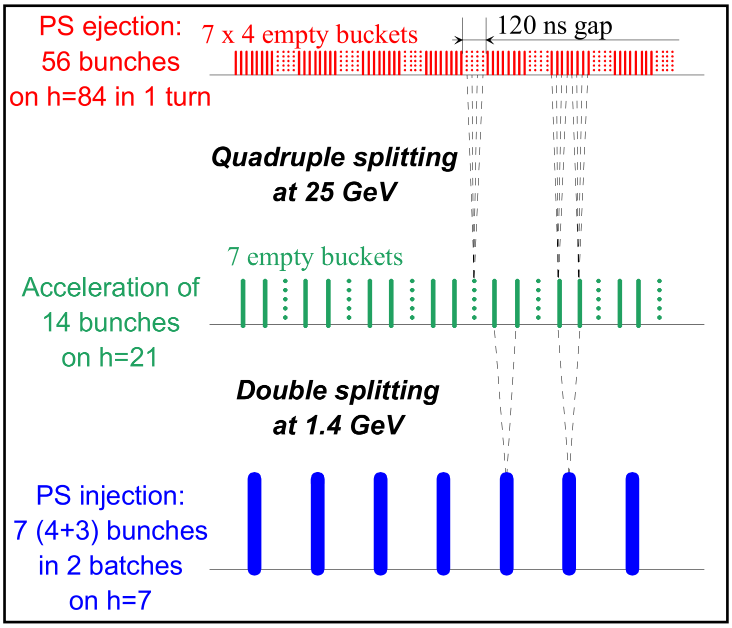

Figure 7.11: Generation of bursts of 25 ns spaced bunches.

7.3 REPERCUSSION ON OTHER BEAMS

The switch of the PSB from a systematic number of five proton bunches per ring to one or two bunches led to a redesign of all RF operations both in the PSB and the PS and renewal of the beam control equipment. Although not fully up-to-date, an extensive analysis of the PS complex' operational beams after the conversion to LHC may be found in [5]. Tab. 7.2 summarises the characteristics and modes of operation in typical cases.

These fundamental changes prove favourable to the quality of most of the beams because of the following main advantages.

In the PSB:

- The longitudinal acceptance is increased by the use of harmonic 1, thus eliminating a long-standing bottleneck.
- Longitudinal coupled bunch instabilities, which were cumbersome to circumvent, are no longer possible with a single bunch per ring.
- Controlled longitudinal blow-up (using the C16 RF system) and bunch splitting (using the C2 and C4 systems) are now possible.
- The rise-times of the PSB ejection, recombination and PS injection fast kicker magnets are now relaxed to at least 90 ns (instead of 60 ns when the PSB was operating with 5 bunches).

In the PS:

- With one bunch per PSB ring, schemes to fill a fraction of the PS with four PSB rings can be designed (LHC, antiproton production beam for the AD, etc.).
- The very long bunches (50 to 100 m in both PSB and PS) cover a narrower frequency spectrum, so that they do not probe potentially harmful impedances at high frequencies.
- With an injection energy of 1.4 GeV, space-charge is reduced for all high intensity beams, such as SPS fixed target physics, AD production, etc.. Moreover, beam losses between PSB and PS are reduced due to the smaller beam size of the highest intensity beams.

Table 7.2: Typical operational beams and ways to produce them.

	ISOLDE	**LHC nominal**	**SPS physics**	**SPS ion physics**	**East Hall**	**AD p-bar production**	**AD test**
Particle	p	p	p	Pb^{82+}	p	p	p
PSB extraction				(Pb^{53+})			
Energy/nucl. [GeV]	1/1.4	1.4	1.4	0.145	1.4	1.4	1.4
Charges/ring	8×10^{12}		8×10^{12}	5×10^{9}	$\sim 3 \times 10^{11}$	5×10^{12}	4×10^{10}
Harmonic number	1	1	2	4	1	1	2
Bunch splitting.	no	no	yes	no	no	no	no
Rings used	4	4+2	4	4	1	4	1
PSB batches	1	2	1	1	1	1	1
Bunch spacing at PS injection [ns]			286	259		286	
Bunch length [ns]	190	190	176	90	50-120	190	140
Kicker rise/fall time maximum [ns]	382		110	169		96	
PS injection							
Charges		10^{12}	3×10^{13}	2×10^{10}	$\sim 3 \times 10^{11}$	2×10^{13}	2×10^{10}
Harmonic number		7	8	16	8	8	16
Number of bunches		6	8	16	1	4	1
Bunch splitting at low energy		$h7 \rightarrow h21$ (1.4 GeV)	$h8 \rightarrow h16$ (2.75 GeV)	no	no	no	no
PS extraction							
Energy [GeV]		25.1	13.1	19.1	23.1	25.1	2.74
Harmonic number		84	420	16	debunched	20	16
Number of bunches		72	420	16		4	1
RF gymnastics before extraction		2 double splittings + rotation	debunching rebunching	none	debunching & slow extraction	*h* sweep from 8 to 20 and rotation	none
Comments			often lower intensity	in-flight transfer C02-C04 in PSB	lower intensity often required		1 bunch discarded at PS injection

7.4 PS BEAM CONTROLS

7.4.1 Capture, low energy splitting and acceleration

For capture at 1.4 GeV and acceleration up to 25 GeV, each of the 10 PS ferrite cavities is driven by its own Direct Digital Synthesizer (DDS), (called Multi-Harmonic Source or MHS), clocked on harmonic 128 of the revolution frequency. The phase and radial loops control the $h = 128$ clock (Fig. 7.12).

The open loop revolution frequency is derived from a look-up table controlled by a real-time B-field measurement (B-train). After digital multiplication by 128, the open loop frequency word is added to a digital correction signal generated by the phase and radial loop to control the main DDS on $h = 128$. The phase and frequency for each cavity is given by its MHS, driven by the $h = 128$ clock and using the instantaneous value of the harmonic provided by a function generator.

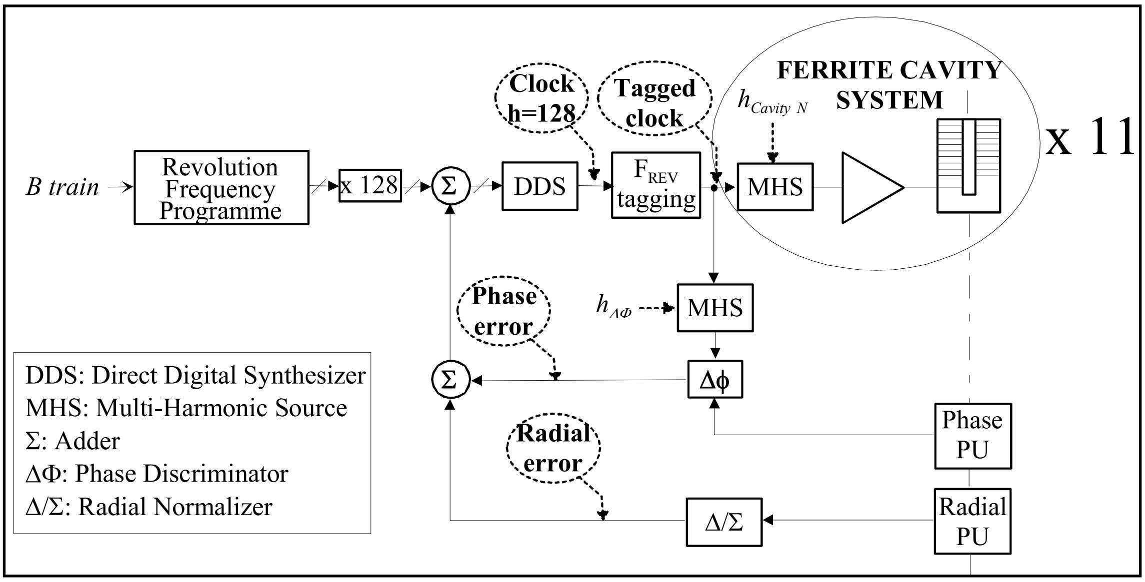

Figure 7.12: PS beam control used from injection till the beginning of the 25 GeV gymnastics.

Phase measurement is done at an harmonic defined by a specific function generator, driving a dedicated MHS. Switching time is negligible with respect to the time response of the loop. Timings control the precise moment when the harmonic number is changed. In these conditions, coherent (n=0) bunch phase oscillations are avoided up to the highest intensities required by operational beams, which is essential for reliable performance of the whole process.

7.4.2 Beam Gymnastics at 25 GeV

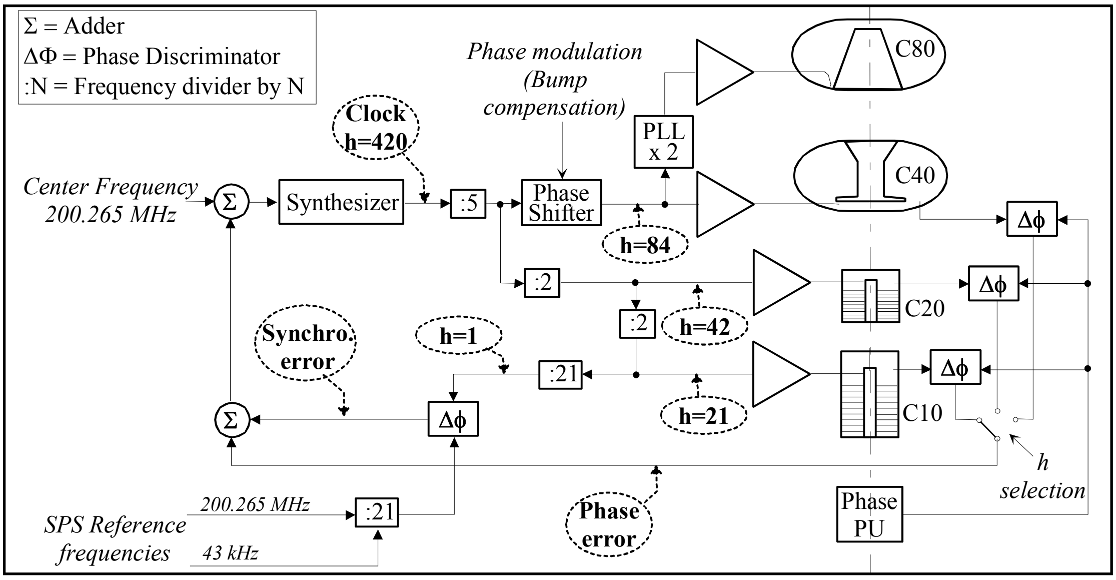

Figure 7.13: PS beam control used during the gymnastics at 25 GeV.

At 25 GeV, a different beam control (Fig. 7.13) takes care of generating the sine waves exciting the 13, 20, 40 and 80 MHz cavities which are outside the frequency range of the beam control used previously in the cycle. The oscillator controlled by the phase loop operates on harmonic 420 of the revolution frequency. The 40, 20 and 13 MHz RF are conveniently derived by division (respectively by 5, 10 and 15), while the 80 MHz is obtained by multiplication by 2 with a Phase Locked Loop (PLL). During all gymnastics, a beam phase loop is active, which is switched from h = 21 to 42 and 84 (25ns bunch spacing) or h = 14, 28 and 84 (75 ns bunch spacing).

In the last 7 ms before ejection, a phase shifter serves to keep the beam energy constant while the orbit length is increased by the action of the pulsed extraction bump.

The orbit bump which moves the beam towards the extraction septum has a deleterious effect on the process of bunch rotation. This is compensated by programming the phase of the 40 and 80 MHz RF such that the buckets remain at constant energy while the phase at ejection is kept the same from cycle to cycle (phase modulation with a fixed point at ejection). If the mean radial excursion due to the bump reaches a maximum of ΔR in a time T, the orbit may be assumed to evolve according to

$$R(t) = R_{nom} + \Delta R \cdot \sin\left(\frac{\pi t}{2T}\right).$$

Hence, at constant energy, the (angular) RF frequency differs from its nominal value by

$$\Delta\omega(t) = -\omega_{nom} \cdot \frac{\Delta R}{R_{nom}} \cdot \sin\left(\frac{\pi t}{2T}\right).$$

Integrating gives

$$\Delta\varphi(t) = \omega_{nom} \cdot \frac{\Delta R}{R_{nom}} \cdot \frac{2T}{\pi} \cdot \left[\cos\left(\frac{\pi t}{2T}\right) - 1\right].$$

This is the form of the function with which the 40 and 80 MHz RF are phase shifted during bunch rotation. Fig. 7.14 shows the result on the beam phase (top trace) of the compensation of the bump (bottom trace) by a suitable phase modulation (middle trace).

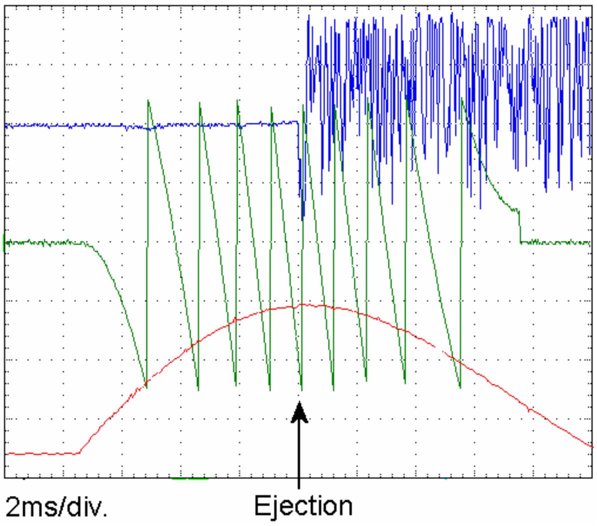

Figure 7.14: Bump compensation before ejection from the PS.

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