EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — A&B DEPARTMENT

AB-Note-2004-050 MD

Pilot Bunch in the LHC Injector Chain

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Abstract

During the 2003 run pilot bunches have been accelerated through the whole injector chain and have been delivered for TT40 extraction tests. The basic machine settings (in PSB, PS and SPS) and the results obtained are reviewed.

Geneva, Switzerland
January, 2004

1. Pilot bunch parameters

Before starting the LHC filling process for each physics coast a low intensity beam will be required to verify the LHC machine settings safely [1,2]. Such beam must be measurable by the beam observation systems of the LHC and its intensity must be such to allow the complete loss at injection without quenching the LHC magnets. For that reason this beam is also called the safety beam. It consists of a single (pilot) bunch, with an intensity of around 5×10^9 p. The pilot bunch can be produced in the injector chain with the required intensity and emittances [3] and with good parameter reproducibility. It has already been delivered for the TT40 extraction tests [4]. The required parameters of the pilot bunch at extraction from the SPS are listed in Table 1.1.

Table 1.1: Required pilot beam parameters at extraction from SPS.

Proton momentum [GeV/c]	450
Number of bunches/PS batch	1
Number of PS batches/SPS batch	1
Number of particles per bunch N_b [10^{11}]	0.05
Circulating beam current [A]	3.5×10^{-5}
Rms transverse normalised emittance $\varepsilon^*_{H,V}$ [μm rad]	<1.0-3.5/<1.0-3.5
Longitudinal emittance [eV.s]	<0.8
Rms bunch length [cm]	<15
Rms energy spread [10^{-4}]	<2.8

2. PSB settings

All beam parameters of the LHC pilot bunch should already be defined and fixed at extraction from the PSB, in contrast to the production scheme for the nominal LHC beam, where the longitudinal bunch characteristics is established in the PS. Therefore a completely different approach is required and a dedicated production scheme was developed and successfully tested already in 2002 [5]. The main ingredients of the scheme are briefly summarised below.

The production of LHC pilot bunches in the PSB is a delicate task for the following reasons: (i) the very low bunch population (0.05×10^{11} protons corresponds to only 5×10^{-4} of the maximum population that can be produced with a single PSB ring); (ii) the very low beam brightness, $N_b/\varepsilon^*_{H,V}$ (the brightness of the largest-emittance pilot bunch is a factor ~300 smaller than the one of a bunch for the nominal 25 ns LHC beam in the PSB); (iii) the small longitudinal emittance (in standard operation with the h=1 RF system bunches with a longitudinal emittance of ~1.5 eV.s are obtained). The LHC pilot bunch parameters at PSB ejection are summarised in Table 2.1.

Table 2.1: Pilot bunch parameters at extraction from PSB.

Beam kinetic energy [GeV]	1.4
Number of bunches	1
Number of particles per bunch, N_b [10^{11}]	0.05
Rms transverse normalised emittance $\varepsilon^*_{H,V}$ [μm rad]	<0.8-2.5 / <0.8-2.5
Longitudinal emittance [eV.s]	<0.3

All beam tests were performed in ring 3 of the PSB using the standard 1.4 GeV magnetic cycle. Ring 3 is at the same vertical level as the PS ring and no recombination kicker is required for the extraction. A three-turn injection, similar to the one used for the nominal LHC beam, served as starting point for the set-up. Experience during the last years has shown that this type of injection is best suited for good reproducibility and stability, which are essential for both the nominal LHC and the pilot bunch beams. Resonance compensation and working point optimisation are less of an issue because the (vertical) incoherent space charge tune spread at injection is by more than two orders of magnitude smaller than that for the nominal beam where $\Delta Q_v \leq 0.5$.

The intensity (brightness) of the Linac2 beam was reduced by a factor 5 as compared to normal operation using the so-called “sieve”. This is a mechanical device installed in the injection line that allows only about 20% of the beam to pass through, without affecting the transverse emittance. Detuning the multi turn injection process further reduced the brightness of the beam in the PSB. The most effective parameters were the steering and the betatron matching of the injection line, the horizontal and vertical tunes of the machine and the fine timing of the “slow” injection bumpers. However, the resulting total brightness reduction was by far not sufficient and more sophisticated techniques, reducing the longitudinal phase space density were applied, using the fact that longitudinal and transverse phase spaces are nearly uncoupled.

Firstly, the RF voltage during the bunching process was lowered, hereby reducing the fraction of the unbunched Linac2 beam that is captured and accelerated. Secondly, controlled longitudinal blow up was applied during the first half of the acceleration cycle to reduce the longitudinal phase space density. The required final longitudinal emittance is then achieved later in the cycle by longitudinal shaving (voltage reduction) with the principal RF system. Applying more or less blow up gives a good control of the longitudinal density and, since there is nearly no coupling between transverse and longitudinal phase spaces in the PSB, the effect is equivalent to a change of the transverse beam brightness. The exact transverse emittances were obtained by using independent horizontal and vertical “shavers”. For each plane the system uses a single correction dipole to deflect the orbit towards an aperture limitation where the beam is shaved in betatron amplitudes.

In contrast to the nominal LHC beam all pilot bunch variants were produced with the second harmonic RF system. Obviously this generates two pilot bunches but only one is being sent to the downstream accelerator chain. The use of h = 2 for acceleration has two advantages from the operational point of view. The second harmonic RF system is naturally better suited to the production of the relatively small longitudinal emittance (first and second harmonics systems have the same nominal voltage of 8 kV) and by accelerating two bunches, the intensity in the machine is doubled hereby relaxing the demands on the dynamic range of various control loops imposed by the low pilot bunch intensity.

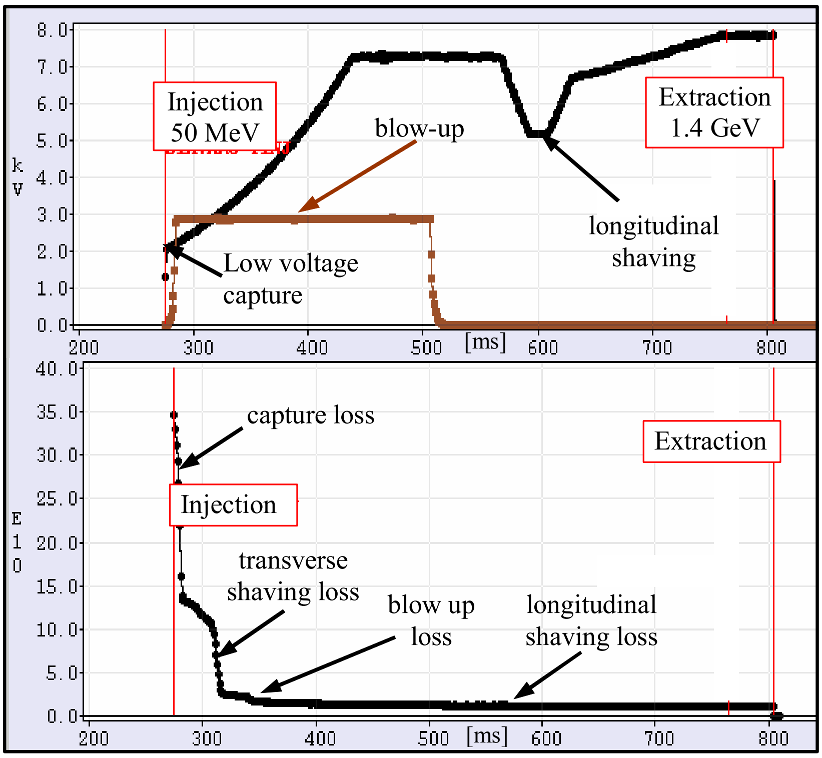

Figure 2.1: RF voltages and beam intensity along the PSB acceleration cycle.

The production scheme is illustrated in Figure 2.1 for the generation of the 0.05×10^{11} – 0.8 μm rad pilot bunch. The upper part shows the voltages of second harmonic and blow-up RF systems along the acceleration cycle. The effects of capture voltage, longitudinal blow up, transverse and longitudinal shavings on the evolution of the beam current are shown in the lower part.

3. PS settings

The PSB/PS beam cycle used for the LHC pilot beam is MDLHC/MDLHC. The beam control is H16li in the PS. Two bunches are thus sent from the PSB and only one (the first) is injected into the PS machine by a reduction of the kicker pulse length. The two-basic-period magnetic cycle used to accelerate the LHC pilot beam from a kinetic energy of 1.4 GeV to a momentum of 26 GeV/c is shown in Fig. 3.1. The beam is injected at C170 and extracted at C1195.

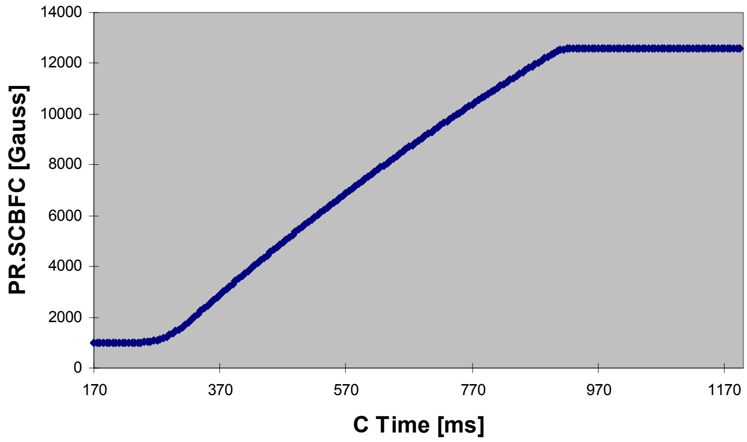

Figure 3.1: PS magnetic cycle. The beam is injected at C170 and extracted at C1195.

Figure 3.2: Evolution of the bunch population with time in the cycle.

The evolution of the bunch population with time in the cycle as measured by the Beam Current Transformer (BCT) is shown in Fig. 3.2 in the case of a beam even slightly less populated than required (~0.03×10^{11} p).

The sensitivity of the radial pick-ups PR.UCT81B and PR.UCT91 has to be set to “1e10” in order to correctly accelerate and cross transition. At high energy, the beam control is changed to h=84 (40 MHz). A bunch rotation by non-adiabatic RF voltage increase on h=84 and h=168 (80 MHz) is performed and the bunch is extracted when is shortest (see Figs. 3.3 and 3.4). The longitudinal emittance is set to ~0.3 eV.s, which is close to the value for all the LHC-type beams, and the final total bunch length is ~4 ns (see Fig. 3.5).

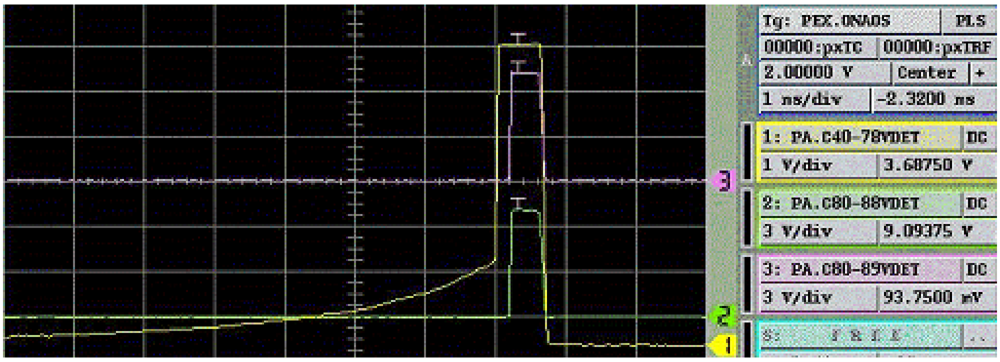

Figure 3.3: Bunch rotation made just before the PS extraction by non-adiabatic RF voltage increase with the 40&80 MHz RF cavities. There is an external start 5.3 ms before extraction (PAX.SBRH84) to start the bunch rotation process. The external start for the 80 MHz cavities is at ~100 μs before extraction.

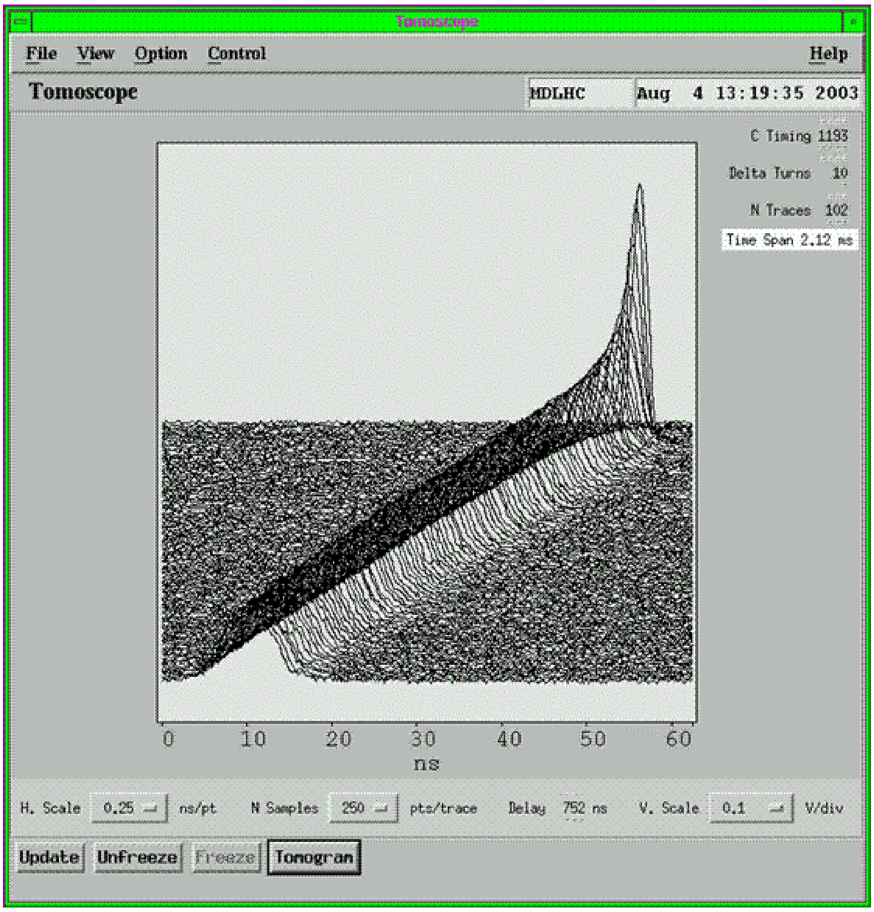

Figure 3.4: Mountain range display of the bunch rotation at PS extraction.

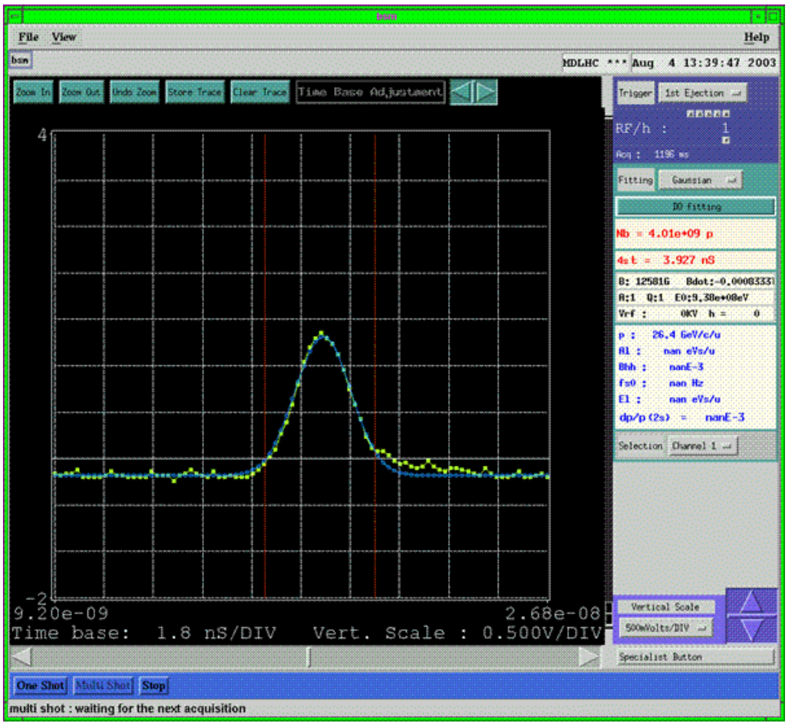

Figure 3.5: Bunch shape measurement at PS extraction.

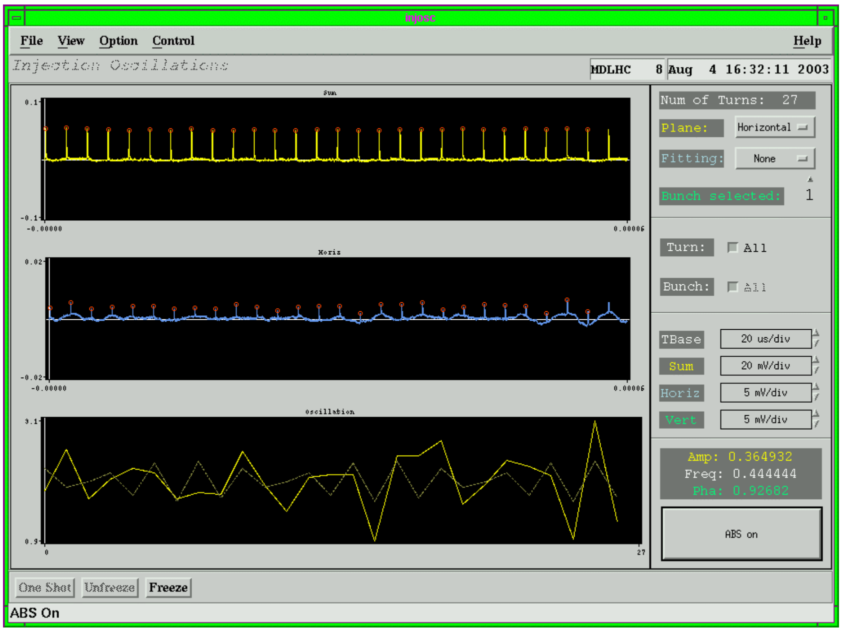

Figure 3.6: Correction of the horizontal coherent oscillations at PS injection. On the bottom graph the highlighted trace is the position at one monitor (obtained by dividing the delta –middle graph- by the sum –top graph) over 27 turns. The other trace is reconstructed after doing an FFT and it corresponds to the amplitude, frequency and phase listed in the box on the right bottom corner.

The horizontal and vertical tunes are set to ~6.22 and ~6.25, respectively (the same coherent tunes as for the LHC beam). Neither octupoles nor skew quadrupoles are used as the intensity is very low and no coherent instability develops. The amplitude of the coherent oscillations at injection is the most critical parameter and it must be corrected down to ±1 mm peak-to-peak (see Figs. 3.6 and 3.7). Note that in order to correct the coherent oscillations at injection it is better to take into account only the first 8 consecutive turns. The machine parameters at extraction are the same as for all the LHC-type beams (see Table 3.1). The Pole Face Winding (PFW) and the figure-of-eight-loop (8L) current settings have also to be the same as for all the other LHC-type beams to guarantee the same extraction conditions and therefore proper injection matching in the SPS. The required and achieved LHC pilot beam parameters at PS extraction are listed in Table 3.2.

Figure 3.7: Correction of the vertical coherent oscillations at PS injection.

Table 3.1: Settings of the main PS extraction elements.

Table GFA	ENABLE
PA.GSCOMP-BSW16	1
PR.GSDHZ15-OC	1
PR.GSDHZ60-OC	1

Table Timings	ENABLE	CCV
PEX.SBSW16	1	1908
PEX.SQKE16	1	3244
PEX.SQKE58	1	2289
PEX.MC-MTG	1	1195
PX.M-STRJ-MTG	1	363

Table	strt	AQN1
PR.SCBFC-C	1195	12581.5
PA.SDFSPS-C	1194	200.2645643

Table	CCV
PE.BSW16	930
PE.QKE16	1250
PE.QKE58	1250
PE.SMH16	28500
PE.KFA71	780

Table	CCV
F16.BHZ117	211.27
F16.BHZ147	184.46
F16.BHZ167	145.61
F16.BHZ377FTS	483.20
F16.DHZ337	0
F16.BVT123	277.88
F16.BVT173	274.23
F16.DVT353	1.20
F16.QDE120	248.20
F16.QDE150	160.60
F16.QDE180	146.60
F16.QDE210S	218.80
F16.QFO105	531.70
F16.QFO135	199.70
F16.QFO165	115.10
F16.QFO205	123.5
F16.QFO215S	241.10
F16.QFO375	257.90

Table 3.2: Required and achieved LHC pilot beam parameters at PS extraction.

Proton momentum [GeV/c]	26
Number of bunches/PS batch	1
Number of particles per bunch N_b [10^{11}]	0.05
Rms transverse normalised emittance $\varepsilon^*_{H,V}$ [μm rad]	<1-3/<1-3
Longitudinal emittance [eV.s]	<0.35
Rms bunch length [cm]	~30
Rms momentum spread [10^{-3}]	1.1

4. SPS settings

Injection and acceleration of such a low intensity beam in the SPS require specific settings for the machine. An alternative scheme would consist in injecting in the SPS a more intense bunch (e.g. a nominal LHC bunch) and in reducing its intensity down to the required value by scraping at 450 GeV/c, before extraction to the LHC. This method (described in [6]) would minimize the amount of tuning required in the SPS to switch from pilot to nominal operation and vice versa but it implies losses and a reduced level of reproducibility in intensity and transverse emittance.

The acceleration of the pilot bunch in 2003 occurred on the cycle used for the nominal LHC beam acceleration (SC 540). The momentum function for that cycle is shown in Fig. 4.1. The long low-energy plateau allows the injection of 4 nominal LHC batches at 0 ms, 3600 ms, 7200 ms and 10800 ms from the start of the cycle. The pilot bunch is injected at 0 ms and acceleration starts at 10860 ms.

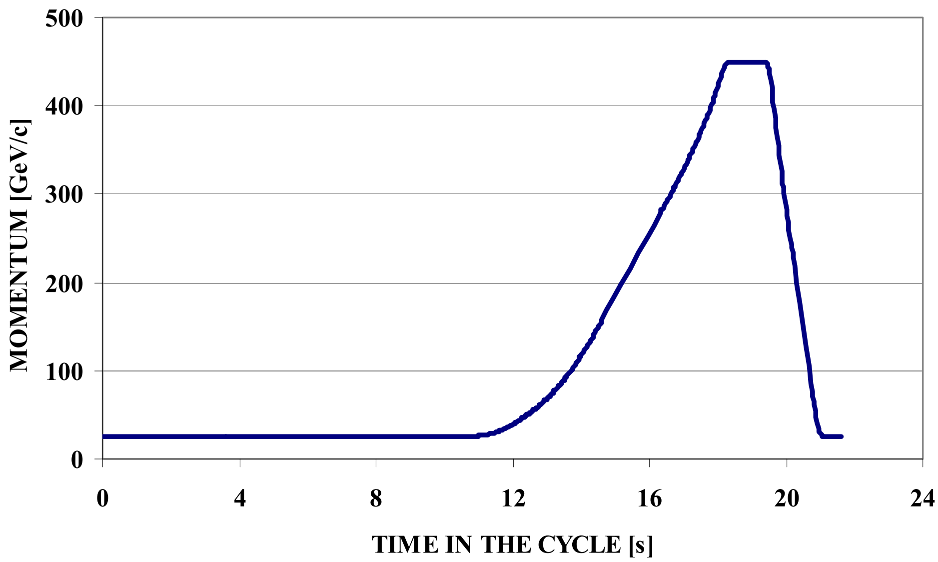

Figure 4.1. Momentum function for the cycle used to accelerate the pilot bunch in the SPS.

The machine working point for the pilot bunch is the same as that used for the nominal LHC beam, i.e. the coherent tunes are q_H=26.185 and q_V=26.13 in the horizontal and vertical plane, respectively. Typical tune trims to be applied at injection with respect to the high intensity settings to compensate for the detuning with intensity are: ΔQ_H= +0.015 and ΔQ_V= -0.03. The required trims decrease with increasing momentum. Because of the low bunch intensity no instabilities are observed and the machine can be operated with low (positive) chromaticity $\xi = (\Delta Q/Q)/(\Delta p/p) \sim +0.03$ in both planes and with the transverse feedback disabled in both planes. The voltage programme is the same as for the high intensity LHC beam and is shown in Fig. 4.2.

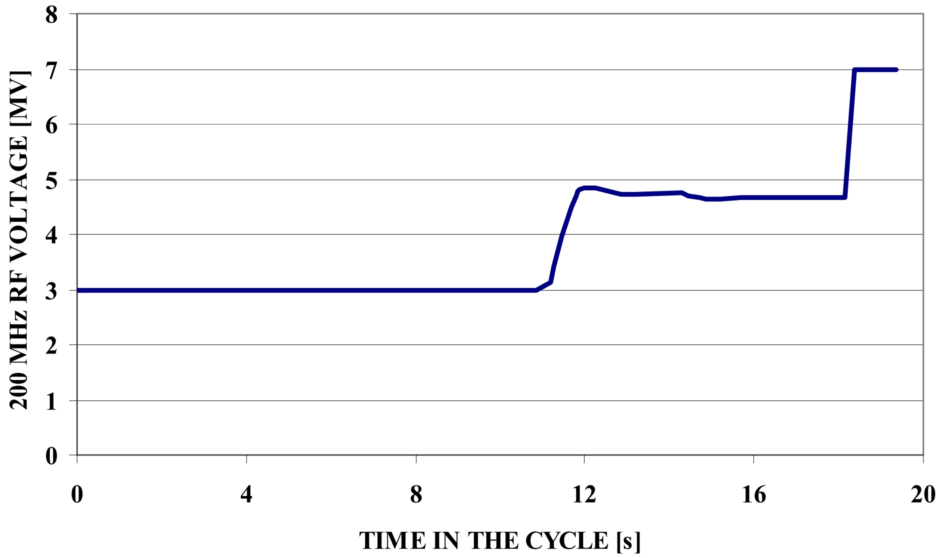

Figure 4.2. Voltage programme for the 200 MHz accelerating system for the pilot bunch acceleration.

Most of the SPS beam measurements (beam position, beam profile, etc.) are gated for a small fraction (< 1 μs) of the revolution period to minimize noise. The gate is synchronous with the revolution train which is distributed to all the SPS auxiliary buildings, the phase or delay of the gate with respect to the revolution train can be adjusted independently for each building but once it is optimized for a beam it should be constant, provided the beam is injected with the same phase with respect to the revolution train. For that reason it is preferred to tune the RF synchronization settings in such a way to preserve for all the beams the same "azimuthal" position in the ring. The reference bunch is the first bunch of the first injected train. This is the bunch displayed in the "SPS mountain range" which provides the longitudinal profile of one bunch over several turns. The position of the first bunch in the mountain range is therefore a diagnostic tool to verify that the beam is being injected properly. This procedure guarantees also the correct synchronization of the beam dump kicker pulse with the beam abort gap once the synchronization has been performed for one beam.

Several RF synchronization settings must be trimmed when switching from LHC nominal injection to pilot injection:

- Injection bucket selector, adjusting the delay of the beam with respect to the revolution clock pulse.
- Injection pulses, adjusting the delay with which the CPS extraction warning – called pre-pulse – is distributed. The delayed pre-pulse is used to trigger the injection kickers and the acquisition of the beam position in all the buildings.
- Phase loop pick-up attenuation. The phase pick-up signal is attenuated for the nominal LHC beam. No attenuation is necessary for the pilot bunch because of its low intensity.
- Sampling gate delay for the phase pick-up. For the nominal LHC beam the sampling gate is not located on the reference bunch but it is opened in the centre of the first LHC train to avoid disturbances due to transients on the first bunches.
- Mountain range pick-up attenuation. It must be reduced (by 36 dB) because of the low bunch population.

The gain of most of the beam diagnostics electronics must be increased to account for the low intensity: typical gains are 40 dB higher than for the nominal bunch intensity. A high sensitivity Beam Current Transformer (BCT 4) must be used for the measurement of the bunch population. BCT4 has a resolution corresponding to 10^8 p as compared to 10^{10} p for the low sensitivity BCT (BCT 3) used for the measurement of the total population of the nominal LHC beam. The tune measurement was performed using the "single bunch" settings.

The control of the injection oscillations is the most critical aspect in the setting-up of the pilot beam. Correction of the first turn-trajectory with respect to the closed orbit down to few tenths of a mm (peak-to-peak) is required particularly for the low-emittance version of the pilot bunch ($\varepsilon^*_{H,V} < 1$ μm rad).

5. Measurements

During the setting-up of the beam for the TT40 extraction tests (25 August 2003) pilot bunches with normalised emittances:

$\varepsilon^*_H = 1.87 \pm 0.08$ μm rad and $\varepsilon^*_V = 2.53 \pm 0.17$ μm rad

were injected in the SPS at 26 GeV/c and accelerated to 450 GeV/c with less than 11 % emittance growth. The values measured at the flat-top were:

$\varepsilon^*_H = 2.07 \pm 0.38$ μm rad and $\varepsilon^*_V = 2.71 \pm 0.21$ μm rad.

The longitudinal emittance of the beam was $\varepsilon_L \sim 0.3$ eV.s at injection and no significant blow-up was measured during the cycle. Similar emittances were measured during the TT40 extraction tests (8-9 September 2003 and 8-9 October 2003).

On November 11, 2003 an additional experiment was dedicated to verify the status of the emittance preservation during transfer and acceleration through the whole LHC injector chain. A pilot bunch with sub-micrometric emittance was transferred through the PS and SPS complex showing negligible emittance growth. Figure 5.1 shows the results of the transverse measurements in the horizontal and vertical planes at the different stages of the acceleration.

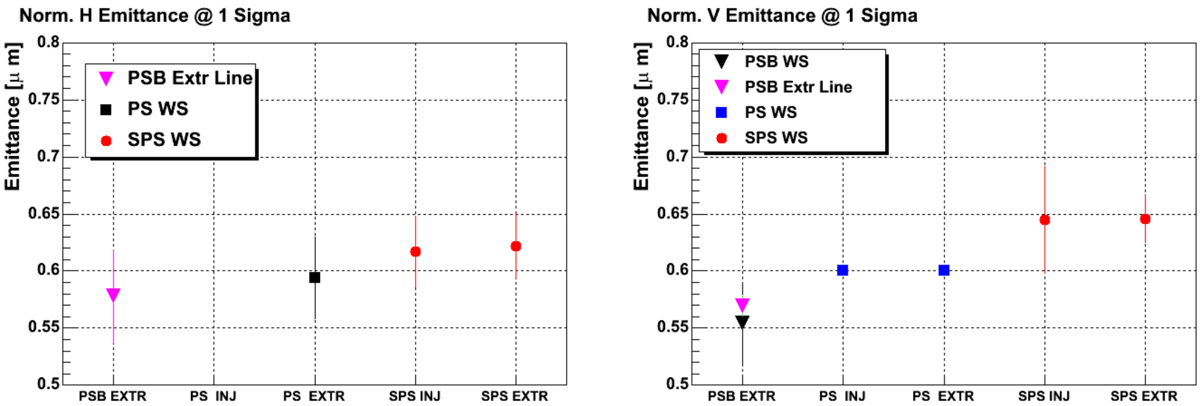

Figure 5.1 Horizontal (left) and vertical (right) emittance evolution of the pilot bunch through the LHC injector chain.

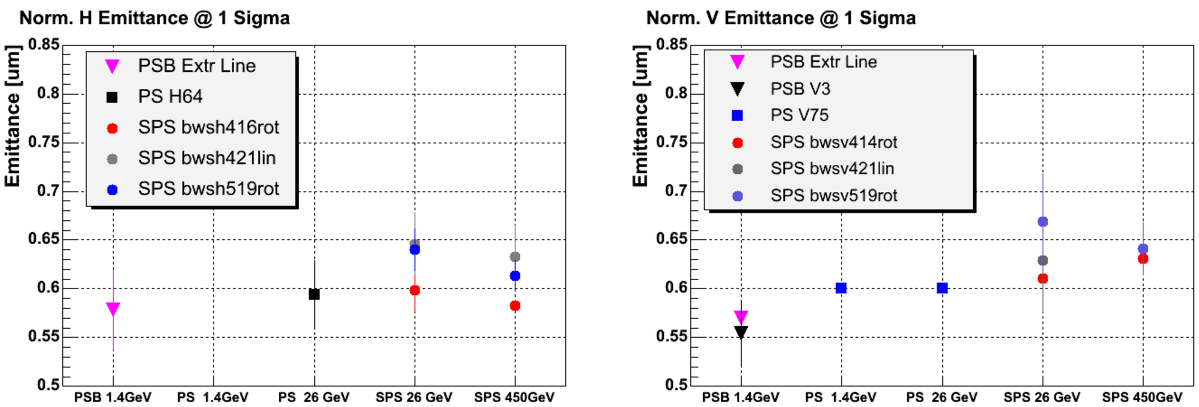

Figure 5.2 Results from the different monitors used to estimate the emittances shown in Figure 5.1.

The profile measurements were performed with wire scanners with the exception of the horizontal measurement in the PSB because the horizontal wire scanner in Ring 3 was broken since the beginning of the run. The horizontal measurement was performed with the SEM wires in the PSB measurement line. No measurement could be performed at injection in the PS and only one measurement could be performed in the vertical plane in the PS at injection and at top-energy (just before bunch rotation) because of a control problem occurred during the machine development session. The plotted data and the error bar represent the average and rms spread of different measurements. The data corresponding to the different SPS Wire Scanners are shown in Fig. 5.2.

The basic parameters for the instrumentation used for the beam profile measurement in the PSB, PS and SPS are listed in the Tables 5.1, 5.2 and 5.3 below.

Table 5.1 Basic parameters for the PSB Wire Scanners during the measurements on November, 11th.

Name	Speed [m/s]	$\beta_{H,V}$ [m]	$D_{H,V}$ [m]	Photomultiplier voltage [V]	Measurement timings (inj./flat-top) [ms]
H3	20	5.8	1.48	Not working	
V3	20	2.9	0	1000	312/840

Table 5.2 Basic parameters for the PS Wire Scanners during the measurements on November, 11th.

Name	Speed [m/s]	$\beta_{H,V}$ [m]	$D_{H,V}$ [m]	Photomultiplier voltage [V]	Measurement timing (inj./flat-top) [ms]
H54	20	12.6	2.3	Not working	
H64	20	12.6	2.3	1000	180/1187
V75	20	11.6	0	1000	180/1187
V85	20	11.6	0	Not working	

For the PSB and PS flying wires, three velocities can be selected (10 m/s, 15 m/s and 20 m/s). The optimal one is 20 m/s since it minimizes the transverse emittance blow up due to the Coulomb multiple scattering caused by the wire passage through the beam. The relative emittance growth reaches 2% at injection in the PSB when operating the devices at 10 m/s [7]. A higher velocity provides less data points for each profile but they are sufficient even in the worst case (PS at extraction with 20 m/s, see Figure 5.3). In the PS the monitors H54 and V85 were broken.

Table 5.3 Basic parameters for the SPS Wire Scanners during the measurements on November, 11th.

Name	Type	Speed [m/s]	$\beta_H/\beta_{,V}$ [m]	D_H [m]	PM voltage (min/max) [V]	Filter set (min/max)	Meas mode	Meas. timing (inj./flat-top) [ms]	Comment
BWS41420	rot	6	99.9/21.3	2.9	1000/1100	2/4	Fast	50/18500	H not working
BWS41620	rot	6	37.4/62.9	-0.1	800/1100	4/6	Fast	50/18500	V not working
BWSL42193	lin	0.4/1	75.2/30.1	2.6	1000/1100	2/5	Fast	50/18500	50/18500
BWSL51731	lin	0.4/1	21.3/101.6	-0.3	800/1200*	0/7*	Fast	50/18500	50/18500
BWS51995	rot	6	81.5/27.5	0.0	1000/1100	4/7	Fast	50/18500	50/18500
BWSL52171	lin	0.4	47.4/49.8	1.9	800/1200*	0/7*	Fast	50/18500	50/18500

* BWSL51731 and BWSL52171 were not used with the pilot bunch in 2003, the PM voltages and filter sets are estimates.

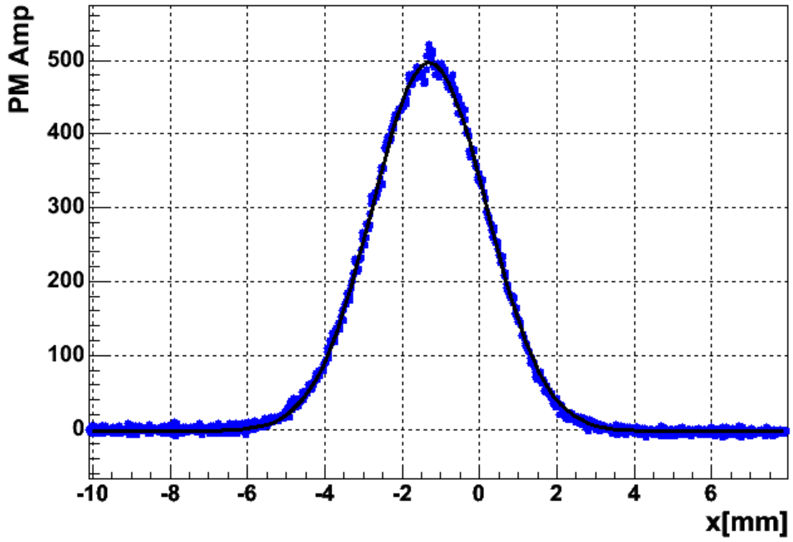

Figure 5.3 Horizontal profile of the pilot bunch at PS extraction. The wire speed for this measurement was 20 m/s.

Two wires in the SPS (BWS41420 horizontal and BWS41620 vertical) were not available when studying the pilot bunch because the wires broke during machine studies with high intensity LHC beams in summer. All these wires have been replaced during the 2003-2004 shut-down period. BWSL42193 has been removed and will not be available in 2004.

The SPS wire scanners are installed in six different locations. At each location there is a device for measuring the horizontal distribution and another one for the vertical distribution. Six out of the twelve monitors have rotating forks and the forks of the remaining six move linearly. All of them provide signals also for the low pilot intensity and should therefore be used in order to have better statistics and data cross check. The linear scanners move slower than the rotational ones and therefore they provide a better spatial resolution. The wire position can be directly measured. The rotational monitors provide fewer points per profile (higher speed) and the wire position in the transverse planes is calculated from the measured angular position. The vertical profiles measured with a linear and a rotational wire scanner at 450 GeV/c in the SPS are shown in Fig. 5.4. The monitors located in a zero-dispersion region are the most accurate in the horizontal plane since they are independent of the momentum spread inside the bunch. Hence, they should be preferred to estimate the horizontal emittance.

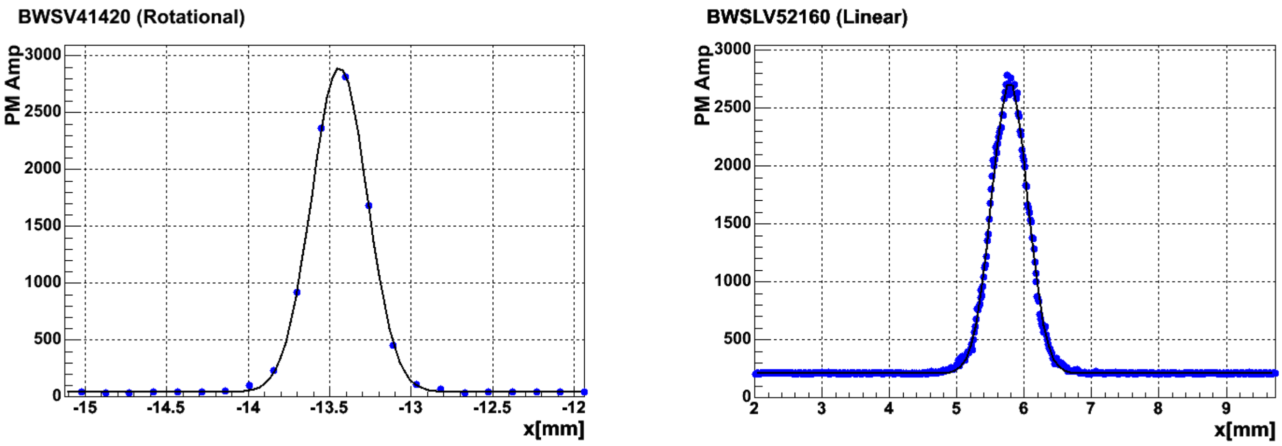

Figure 5.4 Vertical profile of the pilot bunch at 450 GeV/c in the SPS as measured with a rotational (left) and a linear (right) wire scanner.

Between the scintillator and the photo multiplier of each SPS wire scanner there is a set of optical filters, which can attenuate the light fed to the phototube. The filtering level can be varied in the range 0 (minimum attenuation) to 7 (maximum attenuation). The optimal values for the pilot bunch are displayed in Table 5.3. These values are chosen to make the phototube work in a linear region (high voltage between 900 and 1400 V) and to have enough resolution on the output ADC. The ADC has 12 bits (full scale = 4096). Offsets are adjusted before the ADC. In order to profit of the full ADC range it is a good practice to set the high voltage and the filters so that the maximum amplitude lies between 50 and 90 % of the full scale. For the same considerations the maximum amplitude of the profiles in the PSB and PS should exceed 1024, since the 12-bit ADC is used in bipolar mode and has a full scale of 2048. For the SPS wire scanners if a larger signal output is needed, it is better to increase the phototube high voltage rather than decreasing the filtering level. This will reduce the uncertainty related to the noise in the electron multiplication along the photo multiplier electrodes.

The longitudinal emittance of the beam was 0.2 eV.s at injection in the PS and 0.3 eV.s at 26 GeV/c as measured with the PS Tomoscope [8] at C172 and at C1175 on the MDLHC cycle. The results of the bunch tomography are shown in Fig. 5.5.

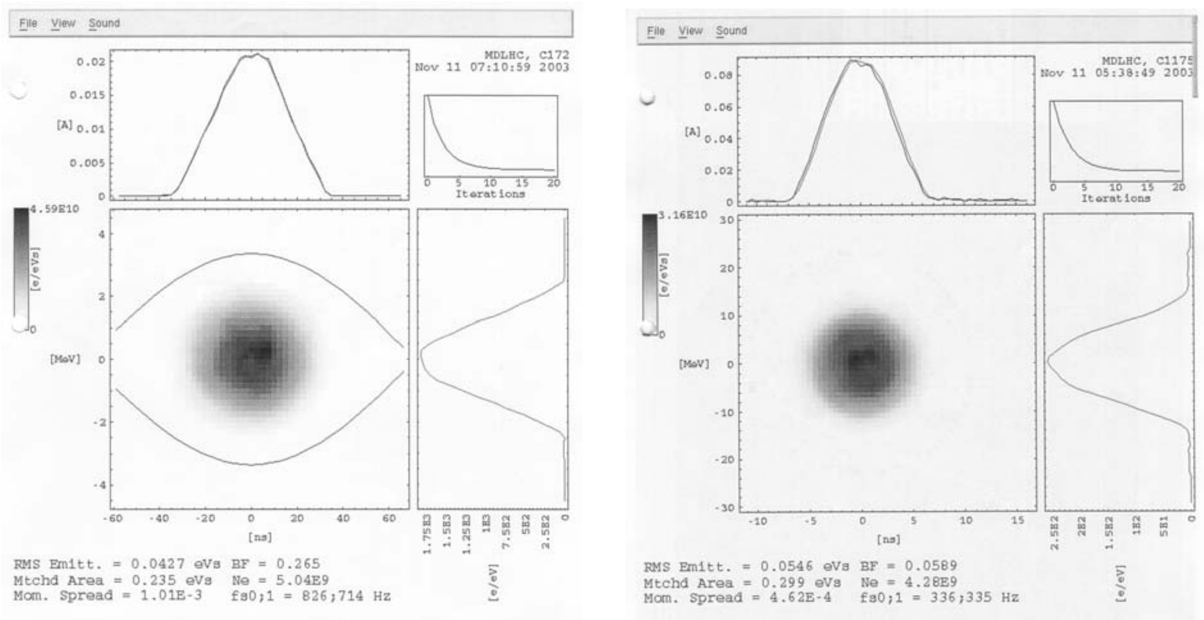

Figure 5.5 Longitudinal phase space tomography of the pilot bunch at injection (C172) – left – and before bunch rotation (C1175, i.e. 20 ms before PS extraction) – right – in the PS.

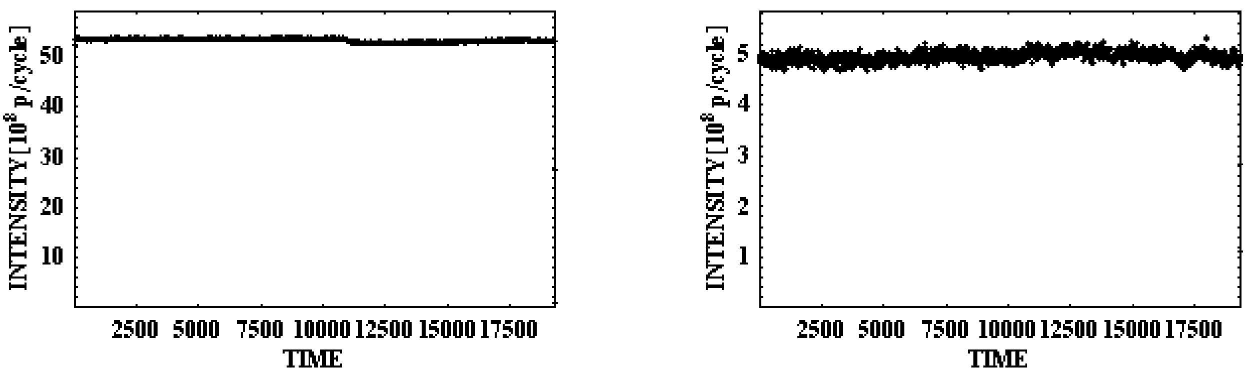

Figure 5.6 Pilot bunch intensity along the SPS cycle (time in ms): average (left) and rms spread (right).

Figure 5.6 illustrates the intensity of the pilot bunch along the SPS cycle averaged over 99 cycles. The rms intensity spread along the cycle is also presented. Less than 2 % losses are observed along the cycle and the rms intensity spread is less than 10% of the average value confirming the good cycle-by-cycle reproducibility of the injector chain.

Finally, it must be noted that techniques to provide a controlled transverse and longitudinal [9] blow-up in the SPS during acceleration have been successfully tested and should allow tailoring the longitudinal and transverse characteristics of the pilot beam to the LHC needs without requiring delicate re-tuning in the pre-injectors.

6. Summary and Conclusions

During the 2003 run pilot bunches have been accelerated through the whole injector chain and were available for the TT40 extraction tests within the specifications and with good reproducibility. The production of the pilot bunch in the PSB is a challenging aspect in the operation of this beam as special techniques are required to produce the very low intensity, low brightness bunch - something that the PSB is normally not asked for. In the PS and SPS the pilot bunch does not represent a challenge from the point of view of the beam stability and the transfer along the LHC injector chain with reduced emittance growth is an indication that the injection errors are well under control (either in terms of betatron and dispersion mismatch or in terms of injection oscillations). The measurement of the beam parameters and in particular of the transverse profiles is certainly a demanding aspect in the operation of this beam.

Acknowledgements

We would like to thank the MCR and PCR operation crews for their assistance during the measurements and Ph. Baudrenghien, D. Stellfeld and U. Wehrle for the setting-up of the capture and acceleration of the pilot bunch in the SPS.

References

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