CHAPTER 38

SPS

38.1 INJECTION

The SPS is the last link before the LHC in the ion injector chain. The LHC filling scheme, described in detail in Chap. 33, implies that each injected PS batch will have to stay a long time, up to 43.2 seconds, on the SPS front porch. This important feature will dictate the choice of the injection parameters [1, 2].

38.1.1 Choice of Injection Energy

In order to minimise the space-charge tune spread on the long injection plateau of the SPS, the highest possible injection energy has been chosen. It corresponds to the maximum PS ejection momentum, 26 GeV/c/charge before stripping, which for Pb^{54+} lead ions yields a kinetic energy $K = 5.9$ GeV/u ($\gamma = 7.31$). After stripping in TT2 the beam rigidity drops to 17.1 GeV/c/charge, see Chap. 37.

The SPS injection kickers had originally been upgraded to accommodate for as short a rise time as 115 ns, for an energy $\gamma = 5.45$, fitting a batch spacing of 125 ns [3]. The higher injection energy of $\gamma = 7.31$ imposes a minimum rise time of 225 ns, which becomes the minimum spacing between PS batches.

The long injection plateau is also the reason of the bunch splitting into bunchlets in the PS as it allows the line density of the beam to be decreased, while preserving its transverse emittances, yielding a much longer longitudinal IBS growth time.

The beam parameters are summarised in Tab. 38.1. IBS calculations have been performed with the Windows version of MAD8 [4], using the Bjorken-Mtingwa formalism [5]

Table 38.1: Summary of injection parameters into the SPS

Momentum per charge	p/Q	17.10	GeV/c/charge
Kinetic energy per nucleon	K/A	5.87	GeV/u
Magnetic rigidity	$B\rho$	57.03	T.m
Reduced energy	γ	7.31	
Reduced velocity	β	0.9906	
Revolution frequency	f_{rev}	42.968	kHz
Bunchlet ion intensity	N_I	6.0×10^7	Ions
Bunchlet charge intensity	N_Q	4.9×10^9	Charges
Longitudinal emittance per nucleon (2 r.m.s.)	$\varepsilon_{//}$	0.025	eV.s/u
Bunchlet length (4 r.m.s.)	τ_b	4.0	ns
Relative momentum spread (2 r.m.s)	$\Delta p/p$	6.5×10^{-4}	
Transverse normalised r.m.s. emittance	$\varepsilon_{H,V}$	1.0	μm
RF frequency (h = 4620, average)	f_{RF}	198.51	MHz
RF frequency (h = 4653, beam passage)	f_{RF}	199.93	MHz
RF voltage	V_{RF}	1.0	MV
Space charge detuning	ΔQ	0.041	
IBS longitudinal growth time	$\tau_{//}$	570	s
IBS horizontal growth time	τ_H	1450	s
IBS vertical growth time	τ_V	2260	s
Duration of injection plateau		43.2	s

38.1.2 Longitudinal Parameters

When filling the LHC, the SPS receives 8, 12 or 13 injections of 8 pairs of bunchlets. The separation between two pairs is 100 ns, while the bunchlets are 5 ns apart.

At injection, a bunch-to-bucket transfer using the existing 200 MHz travelling wave RF system is planned. The nominal longitudinal emittance of the injected bunchlets is 0.025 eVs/u. Below it is assumed that this emittance increases to 0.04 eVs/u along the long flat bottom and during acceleration up to and across transition. The bunch spacing at injection, which corresponds to harmonic number 4653, can be accommodated in the SPS using the technique of fixed-frequency acceleration (see next section).

In the present baseline scheme the injection energy is increased to $\gamma = 7.31$ from the lower value $\gamma = 5.58$ [6] proposed in the previous scheme. This allows a larger emittance at injection for the same RF voltage, which is also advantageous for IBS growth rates. With 8 MV at 200 MHz the maximum possible emittance at injection is now 0.065 eVs/u. A limitation in emittance also comes from the front porch of the accelerating cycle, see next section.

A decrease in peak line density, which can be important for the transverse space charge tune shift can be provided by flattening the bunches using the existing fourth harmonic RF system in the SPS (800 MHz) in the so called bunch lengthening mode.

38.2 ACCELERATION AND RECOMBINATION OF BUNCHLETS

38.2.1 Acceleration

During acceleration the RF frequency for a constant harmonic number changes from 198.51 MHz to 200.39 MHz, while the tuning range of the 200 MHz TW cavities is only (199.5 - 200.4) MHz. The fact that the beam occupies only a part of the ring (6.6 out of 23.1 μs) and that the cavity-amplifier rise-time is about 1 μs allows one to use the technique of fixed frequency acceleration [7]. The idea is to use a non-integer harmonic number by pulsing the RF on at the cavity centre frequency during the beam passage and switching it off in the beam holes to correct the RF phase ready for the next beam passage in the cavities. The phase is adjusted by modulating the frequency via the VCO. At higher energies when the RF frequency is already inside the bandwidth of the cavities, this technique is replaced by normal fixed harmonic number acceleration.

This method has been successfully used for ion acceleration in the SPS fixed target programme since the first lead ion run in 1994 [8].

The length of the acceleration cycle is 10 s. The voltage programmes calculated for emittances of 0.025 eVs/u and 0.05 eVs/u with a filling factor in momentum of 0.95 are shown in Fig. 38.1. As usual the voltage amplitude is decreased during transition crossing ($\gamma_t = 22.8$) to improve transmission. On the flat top the 4 pairs of bunchlets must be recombined into 4 bunches before extraction to the LHC. With a 100 ns bunch spacing this can be done using the 100 MHz RF system installed in the SPS in the past for both p-pbar and lepton acceleration. The small frequency bandwidth (150 kHz) of these cavities limits their application for ions to fairly high energies and in practice to the flat top energy. Three cavities are available and each can provide 330 kV.

38.2.2 Flat Top

To avoid capture losses in the absence of a 200 MHz RF capture system in the LHC (at least in the early stages), the bunch length should be less than 2 ns for the bunch into bucket transfer provided by the main 400 MHz RF system in the LHC.

The corresponding longitudinal emittance at injection into the LHC should then be less than 1.0 eVs/charge or 0.4 eVs/u. The lower limit, 0.7 eVs/charge, is defined in Vol. I, Chap. 21 by the IBS growth rates on the flat bottom in the LHC. If the bunch emittance after all gymnastics is smaller than this low limit, additional controlled emittance blow-up should be planned. Experimental studies with proton beams have shown that the best results (required blow-up efficiency with a minimum loss of particles at the time of excitation) can be obtained using one of the following methods: resonant phase modulation of the 800 MHz voltage, or band-limited phase modulation of the main 200 MHz voltage [9]. In the following paragraphs, two possible schemes for bunchlet recombination which can provide a final bunch emittance in the range (0.24-0.36) eVs/u are considered.

Bunch rotation

In this scheme the voltage of the 100 MHz RF system is used to rotate the bunchlets in longitudinal phase space by 90°. This can be done using two or three cavities with the maximum available RF voltage. This bunch is then recaptured by the 200 MHz RF system. The voltage is increased to 8 MV to shorten the bunch before extraction to the LHC. With two cavities, from simulations with ESME [10], the final emittance (95 % particles) is around 0.36 eVs/u and the rms bunch length is 0.46 ns. The final bunch distribution has two peaks. The time necessary for these manipulations is less than 150 ms.

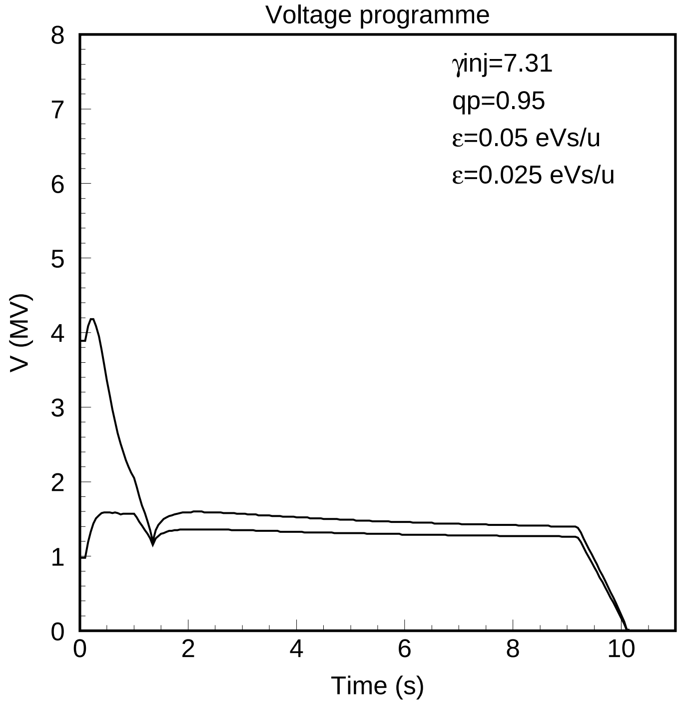

Figure 38.1: Voltage programmes during ion acceleration in the SPS for emittances of 0.025 eVs/u (lower curve) and 0.05 eVs/u (upper curve) with filling factor in momentum of 0.95.

Adiabatic process

In this scheme the voltage of the 200 MHz RF system, used for acceleration, is adiabatically reduced on the flat top to zero or some small amplitude (see below) while the voltage of the 100 MHz is increased to a value sufficient to provide capture of the bunchlet pair with the given initial emittances. The total time necessary for bunch recombination is much longer than for bunch rotation and is around 1.5 s. If no intensity effects are taken into account the total emittance increase in this scheme is very small.

For the LHC beam in the SPS, top energy is known to be the most critical area for beam stability [11] (this has been observed in measurements with proton beams). Even for the relatively low intensity of the LHC ion beam, the impedance of the 200 MHz RF system in the absence of a cavity servo-control system (the RF feedback and feed-forward being switched off) is sufficient to drive the beam unstable leading to rebunching at 200 MHz and some uncontrolled emittance blow-up. This is why in this (adiabatic) scheme it will be necessary to have some controlled emittance blow-up before recombination and to keep the cavity servo-control of the 200 MHz RF system on with some small residual voltage amplitude (for example 100 kV). Starting with an emittance of 0.1 eVs/u per bunchlet (after the controlled emittance blow-up), one gets 0.22 eVs/u for the final bunch emittance (for 95 % of particles). One 100 MHz cavity with 0.33 MV is sufficient. The RF gymnastics for both methods are shown schematically in Fig. 38.2.

38.2.3 The 100 MHz RF System

The 100 MHz RF system was dismantled and removed from the machine following the end of LEP operation as part of the SPS impedance reduction programme and should now be re-installed in the ring. Three 100 MHz RF cavities exist together with the 20 kW final RF amplifiers. All other equipment (infrastructure) should be rebuilt. Each cavity has an R/Q = 230 Ω and an undamped Q = 28000. The damping loops give a reduction in impedance of 40 dB on the fundamental frequency. Beam loading is not important for ion intensities. However to be sure that the fundamental and HOM impedances will not create problems for the high intensity LHC proton beam it is planned to install two non-active cavities in the ring already during the 2003/2004 shutdown for tests. Estimations show that the HOM couplers should be able to cope with the power induced by the high intensity LHC proton beam without additional hardware modifications.

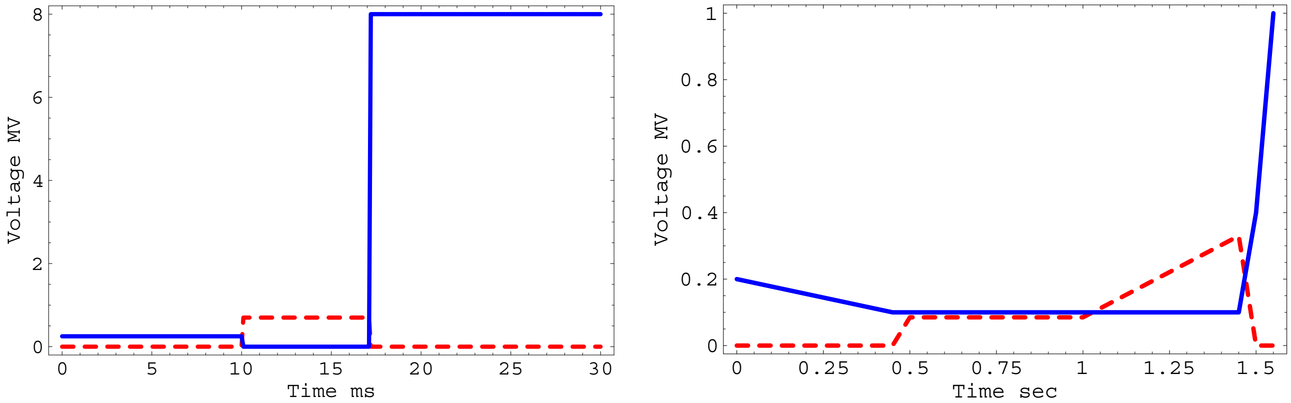

Figure 38.2: Voltage programmes for the 100 MHz (dashed line) and 200 MHz (solid line) RF systems during bunchlet recombination on the flat top for the two schemes: bunch rotation (left) and adiabatic process (right).

38.2.4 Synchronisation

Bunch into bucket transfer was not used in the past for ion injection into the SPS and some new electronics must be built for this purpose to provide synchronisation with the PS [12]. The problem is the same as for acceleration and is connected with the fact, discussed above, that the RF frequency corresponding to the bunch spacing must lie within the 200 MHz cavity bandwidth. Thus, to capture the injected beam, the cavity RF frequency should be locked to the injection frequency while the mean RF frequency is locked to the revolution frequency. For extraction to the correct position in the LHC the beam should be in the right place in the SPS. The time it takes to position the batch in the SPS including fine synchronisation (centring the bunch accurately in the bucket) is about 300 ms. This time can be reduced to 50 ms, in the same way as for LHC protons [13], if the PS batch is injected into the SPS in the position predicted to give the correct position on the flat top. This assumes sufficient reproducibility of the B-field.

38.2.5 Parameters for the Ejected Beam

Taking into account 20 % transverse emittance blow-up and 25 % beam losses, the parameters for the ejected beam are listed in Tab. 38.2 below.

Table 38.2: Parameters of the ejected beam

Bunch ion intensity	N_I	9.0×10^7	Ions
Bunch charge intensity	N_Q	7.4×10^9	Charges
Longitudinal emittance per nucleon (2 r.m.s.)	$\varepsilon_{//}$	0.28	eV.s/u
Bunch length (4 r.m.s.)	τ_b	1.8	ns
Relative momentum spread (2 r.m.s)	$\Delta p/p$	6.3×10^{-4}	
Transverse normalised r.m.s. emittance	$\varepsilon_{H,V}$	1.2	µm
Momentum per charge	p/Q	449.85	GeV/c/charge
Kinetic energy per nucleon	K/A	176.4	GeV/u
Magnetic rigidity	Bρ	1500.3	T.m
Reduced energy	γ	190.4	
Revolution frequency	f_{rev}	43.375	kHz
RF frequency (h = 4620)	f_{RF}	200.39	MHz
RF voltage	V_{RF}	7.0	MV

38.3 OTHER ISSUES

38.3.1 Instrumentation

The SPS instrumentation is up-to-date to measure the ion beams needed for the LHC as it is already now able to measure the lower intensity fixed target indium or lead ion beams. This is in particular true for the orbit measurement systems, beam current transformer and transverse damper [14].

38.3.2 Early Phase Scheme

The early lead ion scheme introduced in 33.1 implies a modification of the parameters for the injection plateau of the SPS. This plateau is now shortened down to 7.2 seconds and one can relax the constraints on the IBS growth times and on the space charge detuning. Although the conservative value of 0.07, dating from the p-pbar era, had originally been retained for the maximum allowed value of the space-charge detuning [15], recent machine developments indicate that much higher values, over 0.15, can be tolerated [16].

Tab. 38.3 gives a list of the injection parameters for the early phase scheme, respectively with a longitudinal emittance of 0.025 and 0.05 eVs/u. Since the longitudinal parameters are unchanged, the discussions on acceleration, flat top and synchronisation presented in section 38.2 above stay valid. The simplification of the early phase scheme in the SPS is the absence of bunchlet merging.

Table 38.3: Injection parameters into the SPS for the early phase scheme

Bunch ion intensity	N_I	1.2×10^8		Ions
Bunch charge intensity	N_Q	9.8×10^9		Charges
Longitudinal emittance per nucleon (2 r.m.s.)	$\varepsilon_{//}$	0.025	0.05	eV.s/u
RF voltage	V_{RF}	1.0	4.0	MV
Bunch length (4 r.m.s.)	τ_b	4.0		ns
Relative momentum spread (2 r.m.s)	$\Delta p/p$	6.5×10^{-4}	1.3×10^{-3}	
Transverse normalised r.m.s. emittance	$\varepsilon^*_{H,V}$	1.0		μm
Space charge detuning	ΔQ	0.081		
Number of bunches per PS cycle		1		
Number of PS injections per SPS cycle		3-4		
Bunch spacing		1.35		μs
IBS longitudinal growth time	$\tau_{//}$	285	-880 (damping)	s
IBS horizontal growth time	τ_H	725	290	s
IBS vertical growth time	τ_V	1130	290	s
Duration of injection plateau		7.2		s

REFERENCES

[1] L. Vos, Considerations about Pb ions at injection plateau of the SPS, Beam Physics Note 60, august 8, 2001

[2] D. Manglunki, Status of what has been and what has to be done on SPS, Proc. of the Workshop on LHC performance, Chamonix XII, CERN-AB-2003-008 ADM, 2003.

[3] J. Uythoven, The New SPS Injection Channel, Proc. of the Workshop on LEP-SPS performance, Chamonix IX, CERN-SL-99-007 DI, 1999.

[4] http://cern.ch/mad/mad8/mad8onWindows.html

[5] J.D. Bjorken and S.K. Mtingwa, Intrabeam Scattering, FERMILAB-Pub-82/47-THY, July 1982.

[6] P. Collier (ed), The SPS as Injector for LHC. Conceptual Design. CERN-SL-97-07 DI, 1997.

[7] D. Boussard, J. M. Brennan, T. P. R. Linnecar, Fixed frequency acceleration in the SPS, CERN SPS/89-49 (ARF), 1989.

[8] D. Boussard, T. Bohl, T. Linnecar, U. Werhle, Non integer harmonic number acceleration of lead ions in the CERN SPS, PAC95, Dallas, 1995 and CERN SL-95-022.

[9] T. Bohl, T. Linnecar, J. Tuckmantel, E. Shaposhnikova Controlled longitudinal emittance blow-up in the SPS as injector and LHC test-bed, CERN AB-Note-03-084 MD

[10] J. MacLachlan, code ESME, http://www-ap.fnal.gov/ESME.

[11] E. Shaposhnikova, LHC beams in the SPS: longitudinal plane, Proc. of the Workshop on LHC performance, Chamonix XII, CERN-AB-2003-008 ADM, p. 44, 2003.

[12] T. Linnecar, SPS RF hardware, I-LHC/LEIR Review, 26-28 March 2003, CERN.

[13] P. Baudrenghien, Beam control for protons and ions, Proc. of the Workshop on LEP-SPS performance, Chamonix IX, CERN-SL-99-007 DI, p. 116, 1999. Synchronisation of the SPS beam with LHC

[14] G. Arduini, private communication

[15] P. Collier, LHC ions in the SPS, 20th LCC meeting, http://cern.ch/lhcp/LCC/LCC_2002-05.html#main2c

[16] H. Burkhardt, G. Rumolo, F. Zimmermann, Investigation of Space Charge Effects in the SPS, Proc. Particle Accelerator Conference PAC'2003, 12-16 May 2003, Portland, Oregon, USA.