Particle Accelerators, 1997, Vol. 58, pp. 91–101
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Printed in India.

PREPARING THE SPS FOR LHC

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(Received in final form 4 March 1997)

The beams that the SPS must accelerate to fill the LHC have stringent requirements both transversely and longitudinally. The single bunch and total intensities have been obtained separately in the past but now have to be produced simultaneously and must be concentrated in a small part of the machine circumference. The transverse emittances will be small as will the allowable blow-up from injection to extraction. Beams with the LHC parameters will not be available in the SPS until the upgrades in the pre-injector chain are finished. Nevertheless a programme of studies is being carried out to examine the different areas where problems might occur. The delicate areas are at injection where single and coupled bunch instabilities have to be controlled in the longitudinal plane and where transverse emittance blow-up is expected, and at top energy where complicated RF gymnastics are required and where longitudinal coupled bunch instabilites can develop on the long flat top.

Keywords: Proton accelerators; Injectors; Emittance conservation

1 INTRODUCTION

The present scheme for accelerating proton beams in the SPS for injection into the LHC has been described and discussed in several references.[1–3] (In the following the acceleration of heavy ions will not be considered). The main bunch and beam parameters[1] are given in Table I.

As a proton-antiproton collider the SPS has accelerated 1.7×10^{11} protons per bunch from 26 to 450 GeV/c in 6 bunches symmetrically spaced around the ring. The longitudinal emittance, important for

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TABLE I Main bunch/beam parameters for the SPS as LHC injector

Parameter		*Injection*	*Extraction*
Momentum	Gev/*c*	26	450
Protons/bunch		10^{11}	
No of bunches		243 in 3/11 of ring	
Bunch spacing	ns	25	
Trans. emittance	μm rad	3.0	3.5
Long. emittance	eV s	0.35–0.5	0.5–1
Bunch length (4σ)	ns	4	1.7
RF system	MHz	200	200/400
I_{RF} in batch	A	0.8	1.2

stability, was larger, being 0.47 eV s at injection and increasing to a stable value of 0.65 eVs during the cycle. In fixed target operation 4.5×10^{13} protons in $\sim$4000 bunches have been accelerated from 14 to 450 GeV/*c*. Considered separately, the intensity requirements for the SPS as injector for LHC have been achieved; what is new is the combined requirement for intense bunches and a high total intensity concentrated in 3/11 of the ring circumference.

As well as the high intensities comes the need for small transverse emittances to obtain the design luminosity in the LHC. The transverse emittance growth allowed between the SPS injection line and the LHC injection line is less than 20%. Typically, in fixed target or collider operation blow-up of the order of 50% is seen between low and high energies.

At extraction the bunch length must be about 1.7 ns to ensure a clean transfer to the 400 MHz LHC receiving buckets. A range of emittance values, 0.5–1 eV s,[4] is acceptable at extraction to the LHC but there is a preference for lower values, the lower dp/p giving effectively more dynamic aperture. The allowed longitudinal emittance increase between injection and extraction, especially with the lower values at extraction, implies careful control of both single and coupled bunch effects during the cycle.

Before describing the various critical areas in the SPS, the proposed acceleration techniques will be outlined. In both cases these are given in summary form – more details are given in separate reports in these proceedings. Various other hardware modifications such as those necessary for the new extraction beam lines and the upgrade of the beam dump are not treated here, but can be found in reference.[5]

2 ACCELERATION PROCEDURES IN THE SPS

The SPS accelerator has six RF systems at the present time. For its use as LHC injector this number will reduce to four and will comprise four 200 MHz travelling wave, TW, cavities as the main accelerating elements, two 800 MHz TW cavities which can be used for controlled emittance increase or extra Landau damping, four new 400 MHz superconducting cavities for bunch compression, if necessary, at extraction, and three 200 MHz standing wave, SW, cavities for longitudinal feedback. The first and second systems already exist, the third will be based on the cavities designed for LHC itself, and the damping system will re-use modified cavities from the lepton acceleration system.

Eighty-one bunches spaced at 25 ns are injected into the SPS at 26 GeV/c using a bunch into bucket transfer from the PS. They are captured by the 200 MHz TW system. During the capture process the bunch blows up to an emittance of about 0.5 eV s and a bunch length of about 4.3 ns. This injection process is repeated three times at 3.6 s intervals, the three batches being placed side by side to fill 3/11 of the circumference. The beam will then be accelerated using probably fixed frequency (variable harmonic number) techniques, to top energy. During the cycle the emittance is increased, if necessary, to 0.6–1 eV s using resonant phase modulation with the 800 MHz TW system. At 450 GeV/c the bunches are compressed to 1.7 ns length to ensure minimum beam loss at injection into the 400 MHz buckets of the LHC. After compression the beam is synchronised with the LHC at both the RF frequency, f_{rf}, and the revolution frequency, f_{rev}, and then ejected. This whole process is repeated 12 times for each of the two LHC rings, the total time involved being approximately eight minutes.

2.1 Bunch Compression[6]

For a clean transfer to LHC the bunches must be compressed prior to extraction to 1.7 ns. For low emittances this is achieved by applying the full voltage, 6 MV, of the 200 MHz TW cavities. For emittances higher than 0.7 eV s more voltage is necessary and this can be obtained most efficiently using a higher harmonic system, in this case

6 MV at 400 MHz. An added advantage of the extra voltage is a lowering of the phase modulation along the batch caused by the transient response of the TW cavities. A new RF system of three superconducting cavities based on the LHC design is foreseen for this extra voltage.

Strong RF feedback is used around the cavities to keep the impedance low and give control of the voltage. The cavity is tuned to just below twice the RF frequency at top energy so that the beam induced voltage is capacitive and focusing. In principle this production of focusing voltage can be achieved without external power. In practice power is needed for beam current compensation during the acceleration process. In fact during acceleration the beam component passes through the cavity resonance and very large powers are required to maintain zero voltage. This is particularly worrying for the RF window. In order to reduce this power fixed frequency acceleration can be used.

2.2 Fixed Frequency Acceleration[6]

The 200 MHz TW system has a risetime of ~ 1 μs. The beam occupies only 3/11 of the circumference leaving a gap of ~ 16 μs which can be used for modulating the phase while no beam is in the cavity. In this way independent control of the bunch spacing and the revolution frequency is provided.

Changing the bunch spacing allows the beam spectrum envelope at each RF harmonic to be moved to different frequencies within the passband of these wideband cavities, ± 0.5 MHz. When the bunches are long at injection and the component at twice $f_{\rm rf}$ is small, the envelope can be moved across the cavity frequency to a value significantly higher and then held there until top energy is reached. The beam current component in the cavity is then minimised and the power required for compensation is also low. At top energy the envelope is moved back towards the cavity resonant frequency after the beam has been moved azimuthally to the correct ejection position and the RF frequency has been locked to the LHC.

This is a complex procedure and machine tests are under way using a prototype cavity installed in the SPS to refine the operational procedures. So far the beam has been accelerated using the fixed frequency technique described and 10% compression has been achieved with 1.5 MV in the cavity and a beam of 7×10^{12} protons occupying one half of the ring. The present limitation comes from the power amplifier.

2.3 Controlled Emittance Increase[7]

After injection the bunch adapts itself to the bucket with some filamentation and the emittance becomes 0.5 eV s. For an emittance of 1 eV s at injection to LHC a controlled blow-up is necessary. Even with smaller emittances an increase to 0.6–0.7 eV s in a controlled way may be desirable early in the cycle to help prevent coupled bunch or microwave instabilities.

An RF system at the 4th harmonic, 800 MHz, already exists in the SPS, having been installed to give Landau damping. Phase modulated voltage from a high harmonic system for controlled emittance blow-up has been used in the past – the question here was whether a low, 4th, harmonic could be used to give good results.

Initial tests have been made with this system at 450 GeV, but at low intensity, and look promising. By exciting the beam over a period of 300 ms, a blow-up of the required amount was achieved without the creation of long tails. These studies will continue to define the optimum parameters, the optimum time in the cycle, and to try and reduce the excitation time.

3 SINGLE BUNCH INTENSITY LIMITATIONS AT INJECTION[8]

The main factors in the choice of the longitudinal parameters are bunch into bucket transfer from PS to SPS, beam loading in the SPS, microwave instability limits in both machines, and the possibilities offered by the new RF systems in the PS, 40 MHz for bunch spacing and 80 MHz for bunch compression. The compromise is a bunch length of 4 ns and emittance of 0.35 eV s.[2,3]

The most critical limitation for single bunch intensity comes from the microwave instability. Direct scaling from experimental data[8] suggests that even a nominal intensity bunch is close to the stability limit. This has been studied over the last two years in more detail although not with the LHC bunches which will only be available much later. Differing estimations of threshold, which were previously obtained using various techniques such as emittance blow-up as a function of intensity or observation of the onset of high frequency signals, have been confirmed. At the same time the low frequency impedance of the SPS has been measured during debunching as 18 Ω.[9] In extrapolating results to determine whether the final LHC bunch will be stable or not, the main problem seems to come from not having a precise enough model of the SPS impedance. An attempt has therefore been made to replace the broadband model of the SPS previously used for estimating beam stability by a more realistic model. A new method to measure the machine impedance using long single bunches with RF off[10] has allowed the dominant resonant sources with low Q and high R/Q values to be observed and, with the help of the laboratory measurements and numerical calculations made by many people, to be identified. The main source of microwave instability is the vacuum ports, 700 cavity-like objects, resonating above about 1.4 GHz.

To raise the instability threshold, ways of shielding these accidental cavities from the beam, using sleeves with RF contacts between the vacuum chambers on either side, are being examined. An alternative method, easier mechanically but not as radical a solution as the first, is to damp them such that their bandwidth is wider than the bunch spectrum. Other possibilities under consideration to raise the threshold of the microwave instability are:

- increase the momentum spread at injection, implying the installation of more RF in the PS,
- decrease the transition energy, γ_{tr} which would raise the η but also increase the dispersion,[5]
- increase the extraction energy from the PS (to 32 GeV/c). This solution[11] is part of a proposition to completely re-design the PS machine.

4 LONGITUDINAL COUPLED BUNCH INSTABILITIES

The sources for coupled bunch instabilities are the fundamental and higher order mode, HOM, resonances in cavities with quality factor,

Q, sufficiently high that the wakefield left by one bunch is seen by the next. In fixed target operation, between 50 and 450 GeV/c, the beam suffers a non-perturbing two-fold longitudinal emittance increase due to these instabilities. For LHC operation the beam is confined to 3/11 of the ring. The TW cavities have high Q resonances for the HOMs but the fundamental, where the long cavity structure is matched at both ends, has effectively a very low Q. This creates two types of instabilities – on the fundamental bunch train instabilities as observed in LINACs can occur, whereas on the HOM frequencies instabilities are of the normal type but are present on a very asymmetric bunch distribution. In this case, theory[12] can give only an upper limit for the growth rate when the ring is filled by bunches of the same intensity as in the batch. Assuming the nominal bunch and a high Q resonator with shunt impedance $R_{\mathrm{sh}} = 1\,\mathrm{M\Omega}$, representative of what can reasonably be achieved in the SPS, and at the frequency which is most efficient for driving the particular mode, growth times of about 10 ms are found at injection and 20 ms at top energy. To combat these instabilities the following steps will be taken:

- cleaning the machine by removal of inessential equipment,
- improved damping of the HOMs in the RF cavities,
- installation of a longitudinal feedback system. Requirements for this will depend on the success of the previous two items. However a system using three of the existing 200 MHz standing wave cavities, at present used for lepton acceleration, with their 60 kW tetrode amplifiers can damp the growth rates given above.
- Additional Landau damping can also help and be introduced by the 800 MHz TW cavities. Decreasing the low-frequency inductive impedance by shielding the vacuum ports, will also lower the coherent frequency shift and improve the natural Landau damping.

5 BEAM LOADING EFFECTS

The TW structures used for acceleration in the SPS are characterised by a filling time of about 600 ns. Application of constant power gives a linear rise in voltage to a maximum in this time, whereas the voltage induced by the beam rises non-linearly after the batch enters and is about 90° out of phase with the applied voltage. Beam loading makes the bunches in the first 600 ns see different voltages from the rest of the batch. This has important consequences at two points in the cycle. At injection the incoming bunches are equispaced and must move to a new equilibrium position. This can cause emittance growth, reduced though by the longitudinal feedback, or even formation of satellite bunches if the injected bunch partially misses the bucket. At extraction the now asymmetrically placed bunches will be sent to the LHC where they must fit into equispaced buckets. This will put more strain on the injection damping system in the LHC and increases the demand for bunch compression before extraction. Clearly the extra voltage provided at 400 MHz by the superconducting RF would reduce this phase distortion.

In both cases a feedforward system can help by programming the RF voltage to compensate the induced voltage. At extraction the system is power limited but the calculated maximum phase displacement, even without the extra voltage of the 400 MHz RF system, ± 14° at 400 MHz, is acceptable. At injection, where the power required is below the maximum available, RF feedback will also partially reduce the effect. In the worst case phase errors of $<25°$ at 200 MHz are expected.

6 TRANSVERSE REQUIREMENTS[13]

To obtain the luminosity in LHC, a very tight emittance budget, 3 μm rad at injection, 3.5 μm rad at extraction, is imposed on the SPS.

6.1 Sources of Emittance Increase

At injection into the SPS a number of sources of emittance growth can be distinguished. These basically divide into two types, those whose effect on the emittance can be reduced by active damping and those where this is not possible.

In the latter category we have dispersion and betatron mis-match effects where the only remedy is accurate measurement and control of the optics in the transfer line and at the injection point into the SPS. Of the 0.5 μm rad allowed total blow-up 0.15 μm rad is assigned to these two and can be obtained by a dispersion mismatch of ≤ 0.25 m together with ≤ 0.15 m for the betatron matching.

Areas where the damper can help are errors in static beam-line steering, cycle to cycle changes in the bending magnets in the transfer line and fast ripple on the injection kicker. The latter will be reduced to $\leq \pm 0.5\%$.[14] Although the damper can reduce these errors by damping the oscillations faster than the tune spread can decohere the beam, it is clearly advantageous to steer and match the beam as accurately as possible and to reduce the ripple, slow or fast, as much as economically possible to reduce the requirements on the damper. The emittance blow-up assigned to all these effects is 0.25 μm rad.

During the cycle the main causes of emittance increase are from resonance crossing, even of high order, due to multipole errors in the machine, and excitation by the damper itself which must be in operation to prevent coupled bunch instabilities, (also a source of emittance increase if not beam loss). The remaining 0.1 μm rad from the emittance budget is assigned to these two effects. Working points in the tune diagram, e.g. just above $q = 0.7$, can be found to accommodate the beam footprint. This is provided that intensity differences between bunches do not cause significant tune shifts due to the direct space charge effect and the coherent effect given by the inductive wall impedance. Good tune measurements must be available so that the beam can be kept at this working point during the cycle.

The excitation by the damper can be kept within acceptable limits by detecting sufficiently small amplitude variations – this defines the resolution of the beam position monitor and electronics, 11 μm horizontally and 5 μm vertically.

It can be seen that to attain all these targets will be a challenging task requiring sophisticated instrumentation.

6.2 Damping Injection Oscillations and Instabilities[15]

The damper has to act faster than the decoherence time, defined by the tune spreads in the beam, to minimise emittance increase. At the same time it has to have sufficient strength to counteract the fast growing instabilities due to the resistive wall, dominant at low-frequencies. The maximum kick required, 3.3 μrad horizontally and 6.2 μ rad vertically ($\beta_{h,v} = 100$ m), is determined by the total injection error and the speed with which it has to operate, 5 MHz, by the fast ripple on the injection kicker.[14] Gain over a bandwidth of more than half the bunch frequency, 20 MHz, is required to damp all possible coupled bunch instabilities. Landau damping with octupoles would require far too high strengths. The existing damper systems can be upgraded to provide these characteristics.

7 INSTRUMENTATION[16]

The operation of the SPS for the LHC beams will push the machine to new limits. Comprehensive instrumentation is essential if the specifications imposed by the LHC are to be respected. Apart from upgrading the electronics in certain monitors, e.g. bunch intensity or SEM grids, to provide batch structure information, and completing the instrumentation in the injection beam lines to make sure the whole line is visible, new instruments such as that foreseen for betatron matching will also be installed.

8 SUMMARY

This has not been intended as a description of all the necessary changes to the SPS required for its new job as LHC injector. Rather an attempt has been made to point out the critical areas where the SPS is at the limit of its performance. Challenges exist both in the longitudinal and transverse planes. To this end machine studies are being undertaken to refine our knowledge of the machine and define the various procedures and hardware required.

The major decision that has to be taken now is whether or not to build and install the 400 MHz superconducting system and use fixed frequency acceleration. If the longitudinal emittance can be kept well under control, both from single bunch and coupled bunch effects, then this system will not be necessary and the acceleration procedure can be significantly simplified. As a result however, the longitudinal damping system becomes essential and more strict requirements are placed on other systems in the ring.

Acknowledgements

Many people, too numerous to mention, in the SL division at CERN have contributed to produce the present status of the SPS as LHC injector as summarised here. I would particularly like to thank D. Boussard for many fruitful discussions and E. Shaposhnikova for reading the document and making useful comments.

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