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STATUS OF THE LHC PROTON BEAM IN THE CERN SPS

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1 LHC PROTON BEAM IN THE SPS

The SPS is the last element of the injector chain for the LHC. It will accelerate 26 GeV/c protons delivered by the PS to 450 GeV/c before extraction to the LHC via the two (each ~ 3 km long) transfer lines TI2 and TI8.

The main parameters of the nominal LHC beam in the SPS are presented in Table 1.

Table 1: Main parameters of the LHC beam in the SPS

Momentum [GeV/c]	26	450
Revolution period [μs]	23.07	23.05
Tunes (H/V)	26.19/26.24	
Gamma transition	22.81	
Max. n. of batches	4	
n. bunches/batch	72	
Nominal I_{bunch} [10^{11} p]	1.1	
Peak current [A]	1.4	1.4
Bunch spacing [ns]	24.97	24.95
Full bunch length [ns]	4	1.74
Batch spacing [ns]	224.7	224.6
r.m.s. $\varepsilon^*_{H,V}$ [μm]	3	3.5
ε_L [eV s]	0.35	0.5 - 1

The total number of particles accelerated per pulse is about 2/3 of the maximum accelerated in fixed target mode (4.81 x 10^{13} p/pulse) [1] but the 200 MHz peak current is as high as twice the corresponding value for the fixed target beam (0.73 A) because less than half of the SPS ring is filled by the LHC beam.

The nominal bunch intensity has already been accelerated in the SPS during p-pbar operation, albeit with different longitudinal emittance and bunch length [2]. Measurements performed in 1999 showed that the threshold for the onset of the microwave instability for an LHC-type bunch was 0.6 x 10^{11} p, almost half the nominal intensity [3].

The above considerations together with the tight emittance budget both for the longitudinal and transverse planes evidence the challenging aspects in the production of the LHC nominal beam in comparison with the past SPS operational experience.

2 THE LONGITUDINAL PLANE CHALLENGE

In the longitudinal plane the main concern in the SPS is to transfer the high intensity beam to LHC with particle losses well below the quench limit. For these to be less than 1% with optimum SPS-LHC matching conditions (in the absence of a 200 MHz capture RF system in the LHC) one needs a longitudinal emittance smaller than 1 eVs and a phase error less than ± 0.2 ns. The energy error between the two accelerators is expected to be below 50 MeV.

With the LHC beam in the SPS a continuous decay of the peak detected signal, accompanied by beam loss, was observed along the flat bottom. In the past, longitudinal emittance blow-up has been caused by single bunch microwave instability, coupled-bunch instabilities and RF noise. In this case successive reductions of RF noise did not visibly improve the situation.

The impedance reduction program in the SPS was almost totally completed during the long shutdown 2000/2001. This included removal of lepton equipment (two RF systems, extraction and injection elements) and shielding and partial removal of many kickers and septa. However the main source of microwave instability was found to be the impedance of the almost 1000 pumping ports - cavity-like objects distributed around the ring. Shielding these elements involved displacement of 400 main dipoles in the ring [4]. Measurements with a single bunch done in 2001 [5] demonstrated significantly improved bunch stability seen both as a decrease in bunch lengthening with intensity by a factor 7 and by the absence of high frequency signals up to the nominal bunch intensity. Measurements with LHC beam on the flat bottom showed a clear increase in beam lifetime and absence of losses.

The disappearance of uncontrolled longitudinal emittance blow-up due to the microwave instability enhanced other instabilities because of the denser bunches. The impedance of the main RF system around the fundamental (200 MHz) frequency was always understood to be a serious problem not only for beam loading but also for coupled-bunch instabilities.

From the start of operation in 2001 each of the four 200 MHz wideband Travelling Wave Cavities was equipped with both feed-forward and one-turn-delay feedback systems working in parallel [6]. These have been designed to both reduce impedance generally and also compensate the transient beam loading at the beginning of the batch. For the nominal bunch current, the beam induced voltage can rise along the batch, without compensation, to 6 MV within ~ 800 ns, comparable to the maximum RF voltage available. At a quarter nominal intensity, with 1.5 MV beam loading voltage expected without compensation, we have measured under worst case conditions a residual voltage of only ± 160 kV along the batch. The main contribution to the phase error at extraction to the LHC, apart from synchronization errors, comes from this residual beam loading. Measurements in 2001 on the flat top at half nominal intensity, with 6.7 MV @ 200 MHz and 200 kV @ 800 MHz, gave a bunch-to-bunch phase error of ± 60 ps.

To fight the strong coupled-bunch instability (dipole mode) observed on the flat bottom, at the end of the year a prototype bunch-by-bunch feedback using the main RF system was installed. This successfully stabilised the half nominal intensity beam (maximum available in 2001) on the flat bottom but was not yet working during the ramp and on the flat top. Up to maximum energy the coupled-bunch instabilities (probably not only due to the 200 MHz impedance) were cured by increased Landau damping using the 800 MHz RF system, the phase shift being programmed in bunch shortening mode.

As a result of all these measures, the longitudinal emittance at the end of the cycle was just below 1 eVs with half the nominal beam intensity.

3 THE TRANSVERSE PLANE CHALLENGE

When the conceptual design of the SPS as LHC injector was carried out [7] the expected main sources of transverse emittance blow-up were:

- Betatron and dispersion mismatch at injection.
- Injection errors: affecting the whole batch (e.g. due to ripple in the current of the power supplies feeding the transfer line magnets) or part of it (e.g. due to the finite rise-time of the injection kicker or to ripple in its pulse flat-top).
- Resistive wall instability.

An extensive campaign of measurements of the injection line optics and of the PS extraction conditions (Twiss and dispersion parameters) allowed reducing the blow-up after filamentation due to injection mismatch from more than 100% to about 10 % [8].

During the 2000-2001 shutdown the injection kicker was modified in order to reduce the rise-time (0-100%) to less than 220 ns and to reduce the flat top ripple below ±0.5%. Measurements performed in 2001 seem to indicate that the rise time is still larger than 250 ns.

The ‘SPS damper’ (combining the functions of injection oscillation damper and of transverse feedback to fight transverse coupled bunch instabilities) has also undergone major changes to cope with the requirements for the LHC beam. The overall bandwidth was extended from 6 MHz to 20 MHz in order to damp all the possible coupled bunch dipole modes [9]. The operation of the new power amplifiers proved to be more difficult than expected and at the end of the run only half of the planned kick strength could be obtained routinely. Improvements in the power protection circuits will allow running in 2002 at the nominal kick strength on a regular basis.

Since 1999, when the first LHC-type beams were available from the SPS injectors, another important source of instabilities and beam blow-up has been evidenced: the beam induced electron-cloud. This is generated by multipacting of the electrons produced by the residual gas ionisation as a consequence of the bunch intensity and spacing of the LHC beam [10]. Beam Induced Multipacting (BIM) generates important pressure rises (by more than a factor 10) and low-frequency distortion of the signal provided by electrostatic pick-ups used to drive the transverse feedback. The upgrade of the latter during the 1999-2000 shutdown included the implementation of a new 120 MHz electronics for the pick-ups with the aim of filtering out the low frequency component.

In 2001 the threshold for BIM was $I_{bunch}= 0.3 \times 10^{11}$ p. The electron cloud mainly develops in the tail of the batch and couples the motion of subsequent bunches in the horizontal plane (coupled-bunch modes up to a few MHz). In the vertical plane the electron cloud couples the motion of the head and of the tail of the bunch (single bunch instabilities at about 600 MHz). The rise time for the horizontal instability is a few tens of turns (comparable with the expected damping time) and it is quite insensitive to bunch intensity [11]. In a linear machine with low positive chromaticity and without transverse feedback the bunches of the tail of the batch blow-up by more than a factor 3 in emittance and losses occur few ms after injection.

The following actions were taken to fight the electron cloud instability (ECI) and control the emittance blow-up:

- The transverse feedback was carefully optimised, in particular in the horizontal plane where the modes excited by the electron-cloud are within the bandwidth of the system.
- The chromaticity was set to $Q'=(\Delta Q/Q)/(\Delta p/p) = +0.5(H)/+1.5(V)$, particularly in the first part of

the ramp when the bunch length is getting shorter and the electron density is increasing.

- A new working point (Q_H=26.19/Q_V=26.24) was chosen as compared to that (Q_H=26.62/Q_V=26.58) used for high intensity fixed target operation in order to minimise the growth rate of the resistive wall instability.
- A feed-forward for the correction of tune and chromaticity was implemented to adequately control these parameters throughout injection and acceleration (total length=18.5 s) [12].

As a result of that a batch with I_{bunch}=0.6 x 10^{11} p was accelerated to 450 GeV/c with a transmission efficiency of 87% and with emittances below the nominal ones (fig. 1). This could be achieved also thanks to the small emittance provided by the injectors (just above 2 µm in both planes). The observed blow-up (about 50 %) is mainly occurring in the first and the last part of the ramp in the horizontal plane while in the vertical plane it occurs in the middle of the ramp. The relative contributions of the electron-cloud instability and of other phenomena (large tune spread, proximity to stop-bands) to the residual blow-up observed will be investigated in 2002. The blow-up observed in the emittance is even larger (ε^*_{rms} ~ 4 µm in both planes at 450 GeV/c) when 2 or 3 batches with nominal spacing are injected. This confirms observations performed in 2000 indicating that a gap of a few tens of bunches is not sufficient to clear-off the electron cloud generated by the leading batch [13].

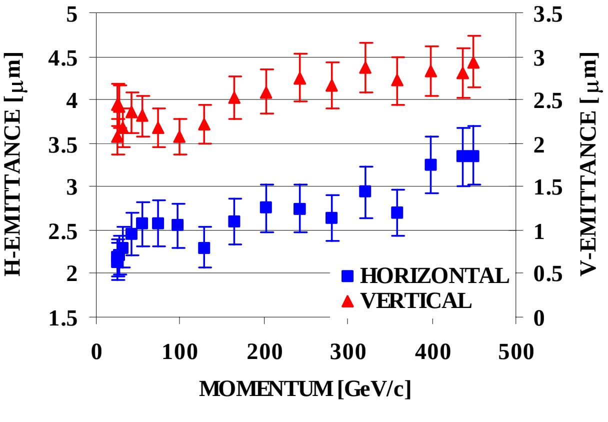

Figure 1: Evolution of the normalised r.m.s. emittance.

4 PRESENT LIMITATIONS AND POSSIBLE CURES

In 2001 the dramatic pressure increase up to the vacuum interlock level was the main limitation preventing stable operation with more than one batch at I_{bunch}= 0.6 x 10^{11} p or with one batch at higher intensities.

The reduction of the Secondary Emission Yield (SEY) is the only viable solution to increase the threshold I_{bunch} for BIM in the SPS without modifying the nominal LHC beam parameters. Measurements performed in 2001 indicate that the threshold for BIM increases with bunch spacing and at 50 ns it is twice that observed at 25 ns. Operation with larger bunch spacing (75 ns) is envisaged as a possible initial scenario for LHC operation.

In May 2002 the SPS has been operated with LHC beam with the aim of reducing the SEY by electron bombardment [14]. After 10 days of scrubbing three batches with I_{bunch} ~ 1.3x10^{11} p could be injected in the SPS with acceptable vacuum pressure increases. The transverse and longitudinal parameters could be kept within the nominal values along the injection plateau, also thanks to the reliable operation of the ‘damper’ at nominal strength.

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