THE LHC PROTON BEAM IN THE CERN SPS: AN UPDATE

G. Arduini, P. Baudrenghien, T. Bohl, P. Collier, K. Cornelis, W. Höfle, T. Linnecar, E. Shaposhnikova, J. Tückmantel, J. Wenninger

CERN, Geneva, Switzerland

Abstract

During the 2001 run the beam-induced electron-cloud, generating dramatic vacuum pressure increases and fast transverse instabilities, was the main limitation in the achievement of the nominal LHC beam intensity in the SPS. Nominal longitudinal and transverse parameters at the extraction energy (450 GeV) could be achieved only with a single batch and with a maximum bunch population of 0.5×10^{11} p. In 2002 the threshold for the onset of the electron cloud in the arcs could be increased from 0.4×10^{11} p/bunch to 0.9×10^{11} p/bunch by means of a dedicated 10-day 'scrubbing' run with the LHC beam. At the end of this period four LHC batches with design bunch population (1.1×10^{11} p) could be injected for each SPS cycle, as foreseen for the nominal filling scenario, without provoking vacuum interlocks. After a series of machine development sessions the LHC beam with nominal intensity could be accelerated to 450 GeV with nominal longitudinal emittance and with transverse emittances close to the design values for the first three batches. The problems encountered with this high brilliance beam and the solutions developed are presented.

LHC PROTON BEAM IN THE SPS

The SPS is the last element of the LHC injector chain accelerating 26 GeV/c protons delivered by the PS to 450 GeV/c before extraction to the LHC. The main parameters of the nominal LHC beam are presented in Table 1 [1].

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

Momentum [GeV/c]	26	450
Tunes (H/V)	26.18/26.13	
Max. n. of batches	4	
n. bunches/batch	72	
Bunch population[10^{11} p]	1.1	
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	< 0.7

Since 1999, when the first LHC-type beams were available from the SPS injectors, electron multipacting was observed as a consequence of the bunch intensity and spacing of the LHC beam [2]. Beam Induced Multipacting (BIM) generates important pressure rises and an electron-cloud develops along the bunch train inducing transverse beam instabilities [3]. In the vertical plane these manifest themselves as a single bunch head-tail instability as a result of the interplay of the electron cloud and of the machine impedance in coupling the motion of the head and the tail of the bunch. The only cure found so far is to run at high positive vertical chromaticity. In the horizontal plane low order coupled bunch instabilities are observed and can be cured by the transverse feedback which has a bandwidth of 20 MHz designed to damp all coupled bunch modes up to the highest (the bunch spacing is 25 ns, see Tab. 1).

In 2001, though cures could be found to control the beam instabilities induced by the cloud, the intensity continued to be limited by the dramatic vacuum pressure rise triggering the beam abort system and preventing stable operation with more than one batch at 0.6×10^{11} p/bunch. Nominal longitudinal and transverse parameters at the extraction energy could be achieved only with a single batch and with a maximum bunch population of 0.5×10^{11} p, i.e. half the nominal population [4].

SCRUBBING RUN

The Secondary Emission Yield (SEY) of the surface of the stainless steel vacuum chambers is the main parameter affecting multipacting for given beam characteristics. Measurements performed both in the laboratory and in the machine indicated that the electron bombardment resulting from multipacting produces a reduction of the SEY ('scrubbing' effect) [5]. In order to confirm that observation, the SPS was operated continuously for ten days with LHC beam at the beginning of the 2002 run. At the end of the 'scrubbing' period the dynamic pressure increase was suppressed by four orders of magnitude and the threshold bunch population for the onset of the electron cloud was doubled from 0.4×10^{11} p to 0.8×10^{11} p in the SPS arcs, corresponding to a reduction of the SEY from 2.2 to 1.6 [6]. This allowed the nominal intensity to be injected without vacuum interlocks.

The success of the scrubbing run was also due to the excellent performance of the transverse feedback in the horizontal plane after the upgrade of its power protection circuits during the shutdown 2001-2002 which allowed running this system at high gain in a reliable way. The reduction of the SEY and the corresponding increase of the multipacting threshold allowed the chromaticity required to stabilize the beam vertically to be reduced.

Subsequent vacuum measurements indicated that de-conditioning occurs when the machine is not operated with the LHC beam but the re-conditioning time is shorter (about 18 hours). 'Scrubbing' is a local phenomenon and the location of the processed area is determined by the

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beam position. The effectiveness of the conditioning depends also on the electron energy that in turn depends on the beam transverse size and in particular on bunch length and bunch charge. An ulterior reduction of the SEY to 1.5 was observed during dedicated machine studies with acceleration to 450 GeV/c when the beam size and the bunch length are getting shorter.

THE WAY TO THE NOMINAL LHC BEAM

Transverse plane

Though the conditioning increased significantly the multipacting threshold, this remained inferior to the nominal intensity and electron cloud transverse instabilities were observed. Particular care was taken to minimize injection errors to allow operation of the transverse feedback system at high gain while avoiding saturation of the amplifiers at injection, where the feedback acts also as an injection damper. It proved to be particularly important to minimize the bunch-to-bunch injection errors affecting the second, third and fourth batches as a consequence of the non-nominal rise time of the injection kicker. At the beginning of the 2002 run the rise-time was larger than 300 ns (0-100%), instead of the nominal 220 ns (the batch spacing is 225 ns – Tab. 1). The injection kicker system [7] consists of sixteen magnets, powered in pairs by eight Pulse Forming Networks (PFN). Twelve out of the sixteen magnets have an impedance of 16.67Ω while the remaining four have an impedance of 12.5Ω and are the slowest elements in the chain. The temporal evolution of the kick delivered by each pair of magnets could be measured in dedicated experiments by kicking the circulating beam. The fine synchronization of the eight PFNs could be measured and adjusted with particular attention to the slowest magnets reducing the kicker rise time to about 250 ns (0-100%). With this configuration only the first bunch of the injected batch and the last bunch of the circulating beam are affected. The damper can effectively damp the oscillation of these bunches in a few tens of turns at least for the first three batches while the damping efficiency appears to be marginal for the fourth batch.

One of the undesired effects of the electron cloud is the baseline distortion of the position signal provided by the electrostatic pick-ups used to drive the transverse feedback. In order to avoid such a phenomenon the Δ-signal from the pick-up is band-pass filtered at 120 MHz (±20 MHz) and mixed with a 120 MHz reference derived from the beam synchronous 200 MHz. This configuration eliminates disturbances due to the electron cloud but is quite sensitive to phase oscillations of the beam, which occur particularly at injection. It was significantly reduced by the implementation of a longitudinal damper.

At the end of the 2002 run the normalised r.m.s. transverse emittances at extraction energy for a beam with nominal bunch population were $\varepsilon^*_{H,V}$ = 2.2(H)/2.2(V) μm for one batch and $\varepsilon^*_{H,V}$ = 3.0(H)/4.1(V) μm for three batches, close to the nominal values (Tab. 1). The values quoted above for three batches correspond to the emittance of the trailing bunches of the last batch where the blow-up due to the electron cloud is larger and very likely are overestimated by 10-20% due to a problem found in the software reconstructing the wire scanner position during the scan. No measurement with four batches was possible because of the breakage of the wire scanner discussed in the next section.

Longitudinal plane

2002 was an important milestone for the acceleration of the full LHC beam in the SPS since, following eight years of preparatory work, nominal longitudinal parameters at extraction energy were obtained for the first time. Indeed the impedance reduction program was completed [1], [8], each of the four 200 MHz Travelling Wave Cavities were equipped with a feedforward and feedback pair [9] and the 800 MHz system was back in operation, ready to provide extra Landau damping. The steps taken are described in detail in [10].

A single batch with intensity three times below the nominal and an emittance of 0.35 eVs develops a coupled bunch longitudinal instability towards the end of the acceleration cycle. This can be cured for nominal intensity if the emittance is intentionally increased above 0.5 eVs and the 800 MHz is used for Landau damping. As a result, the final emittance has been measured in the range 0.52-0.56 eVs, well below the initial target (< 0.7 eVs) [10].

Notwithstanding the campaign to shield the vacuum ports, signals above 2.8 GHz were still visible [8]. These signals were proved recently to be due to pick-up resonances and not due to line density modulation (no change in frequency during debunching). Note that the pick-up cut-off frequency is 2.8 GHz.

Even with the significant reduction of inductive impedance, at least a factor 2.5, the residual impedance (~ 5 Ω) is sufficient to cause loss of Landau damping for single bunches with population above 0.5×10^{11} p. This was verified last year by observation of the Schottky spectrum. Undamped quadrupole oscillations are observed on the flat bottom after injection into an unmatched voltage, in the absence of emittance blow-up due to the microwave instability that we had in the past. These oscillations are not observed for bunch trains of 72 bunches, but could be a problem for the pilot or intermediate beam (12 bunches) required for LHC operation.

In machine studies it was observed [11] that during the normal injection procedure satellite bunches, at 5 ns spacing from the main bunches, were created. This seems to be due to uncaptured particles at injection drifting around the ring and then being recaptured. The situation is worse when the injection voltage is raised from 700 kV to 2 MV. These satellite bunches would remain and be injected into the LHC where the requirements on their intensity from the experiments are very strict.

The longitudinal damping system needed to cure a low frequency (<2 MHz) dipole mode coupled-bunch instability on the flat bottom [10] is also used to damp the phase and energy error at the injection of the second, third and fourth batch. This is essential to keep the emittance constant for all bunches. Its gain was programmed during the ramp in order to get the best compromise between the damping rate needed and the slow blow-up caused by the noise injected by the electronics.

New ideas for synchronizing the SPS beam onto the LHC reference were tested. The LHC bucket reference is used to synchronize the CPS-SPS transfer so that, at 450 GeV/c, the SPS beam is in correct position for transfer to LHC, thereby minimizing the rephasing in the SPS [12]. The method was tested and the rephasing angle is now less than 4 RF buckets (20 ns). It is hoped to reduce it to less than 1 RF bucket in 2003.

SUMMARY, PRESENT LIMITATIONS AND POSSIBLE CURES

By the end of 2002 LHC beam with nominal intensity was accelerated to extraction energy with nominal longitudinal emittance and with transverse emittances close to the design values for the first three batches. Operation with nominal LHC beam revealed some hardware problems that will require attention and additional investigations in the future:

- marginal injection kicker rise-time. Faster thyratron switches will be installed for the PFNs powering the slowest magnets and a further reduction of the rise time by several ns is expected.
- breakage of the carbon wires in the wire scanners even when in parking position [13]. RF measurements conducted in the laboratory on a wire scanner tank showed high impedance modes at around 700 MHz. The beam-induced RF power is absorbed by the carbon wire and is responsible for the observed failures. Ferrite tiles have been installed in the wire scanner housing to reduce the impedance of the cavity modes and SiC wires have replaced some of the carbon wires providing a larger resistivity and therefore lower dissipation.
- heating of the ferrites of the kickers. Measurements confirmed that the time constant for such phenomena is of the order of a day as already anticipated. This should not be problematic for operation with LHC beam interleaved with other modes as expected in the future.
- instantaneous outgassing of the graphite beam dump absorber. This occurs not only when the beam is dumped onto the absorber at the end of each cycle but also during the ramp. The short time constant (seconds) of the latter phenomenon points to a surface phenomenon like multipacting or surface heating due to RF modes induced by the beam.
- instantaneous outgassing of the beam dump and tune measurement kickers. Here again, the short time constant seems to favour the hypothesis of multipacting or surface heating as being responsible for such phenomena.

A scrubbing run including acceleration to 450 GeV/c is foreseen also for the 2003 run. Attempts will be made to increase the bunch population well above nominal with the aim of increasing the multipacting threshold above the nominal bunch population.

Future studies will focus on consolidating the procedures and the cures found for the LHC beam, on ensuring quality control of the nominal beam before extraction and to provide the low intensity test beams required for the LHC.

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