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TRANSVERSE BEAM DYNAMICS STUDIES WITH HIGH INTENSITY LHC BEAMS IN THE SPS

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Abstract

In order to reach the target beam parameters of the LHC injectors upgrade (LIU), about twice the presently operational intensity of LHC type beams has to be achieved. Although the planned upgrade of the main RF system will occur during the long shutdown, a series of measurements have been performed to assess the beam dynamics challenges with these very high intensity beams on the long SPS injection plateau. Bunch-by-bunch transverse emittance blow-up measurements suggested the presence of electron-cloud. After a period of running with the high intensity beam for a couple of days, a clear improvement of beam quality was observed which is attributed to scrubbing. In addition, a horizontal headtail instability is encountered for the usual operational settings of chromaticity and transverse damper. The stability limit as a function of chromaticity and Landau octupole settings has been explored and will be discussed, together with possible sources of the instability and mitigation strategies.

INTRODUCTION

The LHC injectors upgrade (LIU) project [1,2] is presently implementing a series of major upgrades of the injector complex at CERN in order to achieve the beam parameters requested by the High Luminosity LHC (HL-LHC) project. For the SPS, this includes a major upgrade to the main RF system. The aim is to provide the necessary RF power for compensation of beam loading, which presently limits the acceleration of LHC beams to an intensity about 1.3e+11 p/b due to losses. In combination with impedance reduction measures to improve longitudinal stability, the LIU upgrades of the SPS RF system are expected to enable the acceleration of the future LHC beams with appropriate beam quality for the target intensity of 2.3e+11 p/b at SPS extraction. While such high intensity beams could not be accelerated up to now (at least not the bunch train configurations of interest for the LHC), these beams could already be studied at the injection plateau.

High intensity LHC beams suffer from losses on the SPS flat bottom because the RF buckets are full and the RF power presently available is not sufficient for beam loading compensation [3, 4]. The long injection plateau at 26 GeV/c is also challenging for transverse emittance preservation and beam stability. Space charge effects and the impact of power converter ripple have been investigated [5]. This paper summarises the studies concerning the electron cloud effect and the horizontal instability encountered at injection of high intensity LHC beams.

ELECTRON CLOUD

When the LHC beams with 25 ns bunch spacing had been injected for the first time into the SPS in the early 2000's, strong electron cloud (e-cloud) effects had been observed [6]. In particular, strong pressure rise was observed and the beam suffered heavy instabilities and emittance degradation, as well as losses. Over the years, the situation has gradually improved thanks to scrubbing, i.e. conditioning of the vacuum chamber surface through beam induced electron bombardment. Nowadays, the e-cloud effect is sufficiently mitigated for LHC beams with intensities up to 1.3e+11 p/b. However, the LIU target beam parameters require about twice this intensity. The LIU strategy concerning e-cloud is to rely on scrubbing. Only a small portion of the ring circumference (i.e. the vacuum chambers of focusing quadrupoles) will be coated with amorphous Carbon to suppress the e-cloud effect in synergy with the impedance reduction campaign [2].

A dedicated scrubbing campaign with high intensity LHC beams in the SPS (about 2e+11 p/b) was performed in 2015 for about 10 days [7]. A horizontal instability affecting the third and fourth batch of trains of 72 bunches was observed, which required running with high chromaticity and Landau octupoles. Nevertheless, a clear reduction of the pressure rise was observed along this period and also beam transmission on the long injection plateau could be improved with time before saturating at around 88 %. Detailed studies in the following years have shown that the main origin for losses with LHC beams is coming from insufficient beam loading compensation due to RF power limitations of the SPS 200 MHz main RF system in combination with full RF buckets [8]. These losses should be significantly reduced with the major upgrade of the SPS RF system including rearrangement of the travelling wave cavities into smaller sections for reducing beam loading and the construction of two additional RF power plants as part of the LIU project [1, 2].

In 2018, the studies on e-cloud effects in the SPS continued, but this time the "BCMS" beam [9, 10] with four batches of 48 bunches per batch was used. This beam has smaller transverse emittances and thus higher brightness (almost a factor 2) compared to the standard LHC beam and is thus less critical with respect to losses. From end of May until middle of July systematic measurements of the transverse emittances were performed during several periods with high intensity BCMS beams on the SPS injection plateau. Figure 1 shows a summary of the intensity per bunch and the

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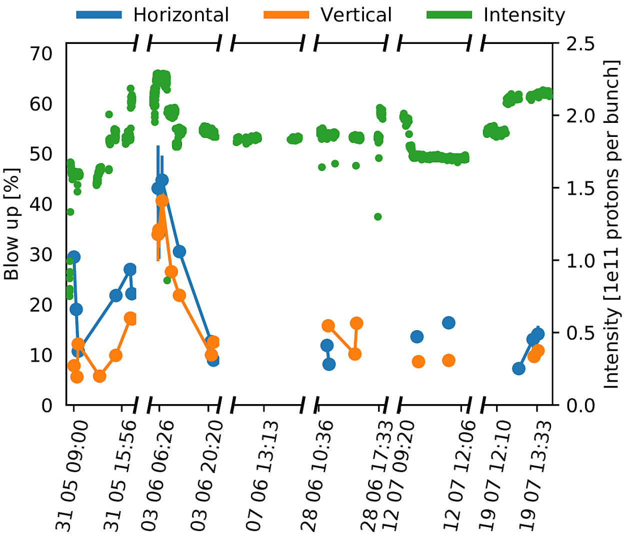

Figure 1: Evolution of intensity per bunch and the horizontal and vertical emittance blow-up of the 48 bunches of the first batch measured after about 17 s storage at the SPS injection plateau for multiple periods in time.

transverse emittance blow-up obtained from wire scanner measurements in horizontal and vertical averaged over the first batch of 48 bunches after about 17 s of storage. Initially about 30 % blow-up was measured in the horizontal plane for an intensity of around 1.6e+11 p/b, but this was reduced to about 10% after a few hours of scrubbing on May 31. During the intensity ramp-up, the emittance blow-up increased again, as this was the first time the high intensity LHC beam was injected into the SPS in 2018. In particular, up to 45 % of blow-up was observed when the intensity reached 2.2e+11 p/b at injection. It is worth highlighting that this emittance growth is due to incoherent effects, since it happens continuously along the flat bottom as shown by measurements with the beam gas ionisation monitor. Although the intensity of the beam was not kept strictly constant, a clear reduction of the blow-up due to scrubbing can be seen from the measurements on June 3. In particular, after about one day of scrubbing, a residual blow-up of less than 15 % could be achieved. This level could be maintained for intensities up to 2.2e+11 p/b through several periods of studies up to middle of July, despite the relatively sporadic operation with these high intensity beams (they were only taken during the indicated periods). For comparison, the LIU target parameters of 2.6e+11 p/b [1] are based on a maximum of 10 % average emittance growth for a flat bottom duration of about 11 s (four batches of 72 bunches with 3.6 s in between injections), which corresponds to an average flat bottom storage time of about 5.5 s. However, it should be emphasised that the e-cloud effect is stronger for the last batches and the blow-up distribution over all batches needs further study.

HORIZONTAL INSTABILITY

As already briefly mentioned above, horizontal instabilities are encountered with high intensity LHC beams on the SPS flat bottom. In 2015, the observations pointed to a coupled bunch instability of the highest coupled bunch mode [7]. Since 2017, an increased transverse damper gain at high frequency is available, but still high chromaticity is needed to stabilise the beam. If the chromaticity is not high enough, the unstable bunches exhibit head-tail motion as revealed by measurements with the SPS head-tail monitor. In particular, oscillation patterns of mode 1 are observed for horizontal normalised chromaticity settings of $0.1 \leq \xi_H \leq 0.3$ and mode 2 for $0.3 \leq \xi_H \leq 0.5$, as shown in Fig. 2.

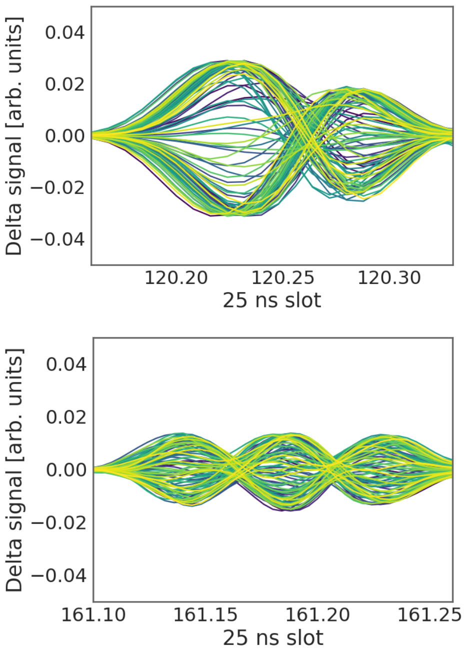

Figure 2: Intra-bunch motion measured with the SPS head-tail monitor for $\xi_H \approx 0.2$ (top) and $\xi_H \approx 0.4$ (bottom).

At the end of 2018, detailed measurements were performed to further characterise this instability. Four batches of 48 bunches per batch of the BCMS beam were used for these studies, i.e. the same beam as used for the e-cloud studies mentioned earlier. The horizontal chromaticity was kept high (normalised chromaticity of $\xi_H \approx 0.5$) for the injection of the first three batches but lowered to $\xi_H \approx 0.05$ just before the injection of the fourth batch while the transverse damper was on during the entire cycle. The LOF Landau octupole circuit of the SPS was adjusted such as to compensate the horizontal detuning with amplitude due to residual non-linearities of the machine (setting of kLOF = -0.2 m^{-4}). With the operational batch spacing of 200 ns the instability is observed for intensities above 1.8e+11 p/b. Figure 3 (top) shows an example of the intensity evolution along the SPS injection plateau in this configuration but for an intensity of about 2.1e+11 p/b at injection, colour indicates the relative bunch intensity. Bunches at the end of the third and of the fourth batch become unstable with the lowered chromaticity, eventually resulting in losses. The rise times associated to this instability are in the order of 100 turns, as can be obtained from the head-tail monitor acquisitions or from the turn-by-turn data of the transverse damper pickups.

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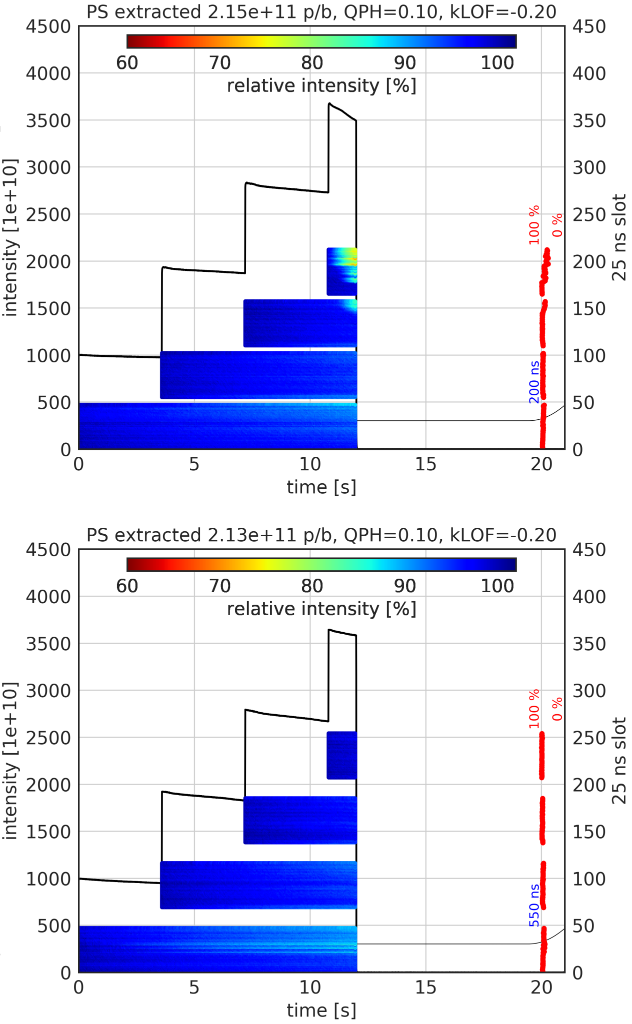

Figure 3: Intensity evolution along the SPS flat bottom for 200 ns batch spacing (top) and 550 ns batch spacing (bottom) for an intensity of about 2.1e+11 p/b. In both cases, the black line indicates the total intensity and the colour indicates the relative bunch intensity according to the colour scale. The bunch slots are indicated on the scale on the right.

A series of measurements was performed in the exact same conditions but varying the batch spacing in steps of 50 ns. Less bunches are affected by the instability when increasing the batch spacing and eventually no instability was observed for a batch spacing larger than 500 ns. Figure 3 (bottom) shows an example for a measurement with 550 ns batch spacing, where all bunches are stable and thus no particular losses of individual bunches are observed.

Finally, measurements of the stability limit as a function of chromaticity and octupole settings were performed. As before, four batches of 48 bunches per batch were injected, where the chromaticity was kept high for the injection of the first three batches and then lowered just before the injection of the fourth batch. It should be mentioned that the SPS octupole scheme was modified in 2018 [11], since in the original scheme the octupoles induced a large Q'' in the Q20 optics [12] used for LHC beams and this restricted their usable strength due to incoherent losses induced by chromatic detuning. In the new scheme much higher amplitude detuning can be reached before suffering from this effect. The results presented here were obtained after the modification of the octupole circuits. Figure 4 shows the obtained stability limits for an intensity of about 1.8e+11 p/b at injection. Positive values of the octupole knob are not shown as they resulted in worse beam stability. As expected, the instability becomes more critical with higher intensity and thus higher octupole strength and/or higher chromaticity is needed to stabilize the beam.

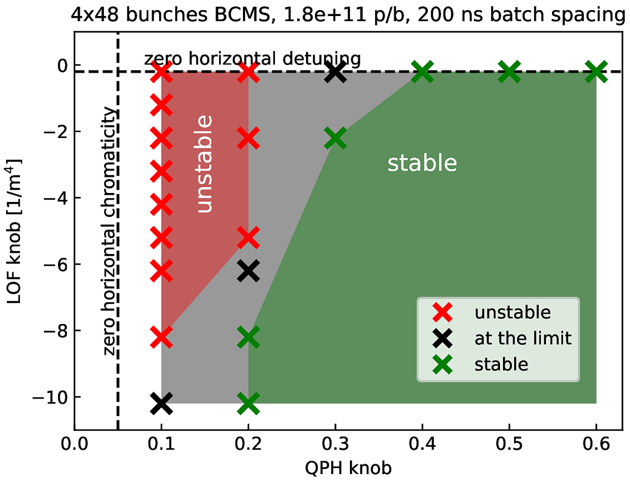

Figure 4: Horizontal beam stability for different chromaticity and octupole settings, where the QPH knob controls the normalised horizontal chromaticity ξ_H and the LOF knob controls the normalised octupole strength. The values for zero chromaticity and no amplitude detuning are indicated by dashed lines. The markers indicate unstable (red), stable (green) and settings where some shots were stable and some unstable (black) as obtained from about 5 shots per setting.

The measurements described above serve as basis to identify the impedance driving this instability through beam dynamics simulations in PyHEADTAIL. A detailed model of the SPS impedance has been developed in the last years and successfully benchmarked with single bunch measurements [13, 14]. Preliminary results indicate that the resistive wall impedance in combination with the impedance of the SPS extraction kickers [15–17] could play a major role. At this point it can also not be excluded that the e-cloud effect plays a role in the instability mechanism.

CONCLUSION

The long injection plateau of the SPS is challenging for high intensity LHC beams with 25 ns bunch spacing due to emittance growth induced by e-cloud effects. Measurements in 2018 have shown that the emittance growth can be mitigated by scrubbing. Furthermore, horizontal instabilities are encountered for intensities above 1.8e+11 p/b and batch spacings lower than 500 ns. The driving impedance and appropriate mitigation measures remain to be identified.

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