PROBING INTENSITY LIMITS OF LHC-TYPE BUNCHES IN THE CERN SPS WITH NOMINAL OPTICS

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Abstract

Some of the upgrade scenarios of the high-luminosity LHC require large intensity per bunch from the injector chain. Single bunch beams with intensities of up to 3.5 to 4e11 protons per bunch (p/b) and nominal emittances were successfully produced in the PS Complex and delivered to the SPS in 2010. This contribution presents results of studies with this new intense beam in the SPS to probe single bunch intensity limitations with nominal gamma transition. In particular, the vertical Transverse Mode Coupling Instability (TMCI) threshold with low chromaticity was observed at 1.6e11 p/b for single nominal LHC bunches in the SPS. With increased vertical chromaticity, larger intensities could be injected, stored along the flat bottom and accelerated up to 450 GeV/c. However, significant losses and/or transverse emittance blow-up were then observed. Longitudinal and transverse optimization efforts in the PSB, PS and SPS were put in place to minimize this beam degradation and succeeded to obtain single 2.5e11 p/b LHC-type bunches with satisfying parameters at extraction of the SPS.

INTRODUCTION

In the frame of the foreseen LHC injector upgrade, CERN is currently probing the brightness limits of the LHC injectors with LHC-type beams [1]. The efficient ramp-up of the LHC performance over the past months is now pushing for additional improvements of the injected proton beam, in particular in terms of bunch intensity and transverse emittance. This contribution presents the studies performed in the injector chain to increase the bunch intensity beyond nominal (1.15e11 p/b) and ultimate (1.7e11 p/b) at extraction of the SPS.

PREPARING HIGH INTENSITY SINGLE BUNCHES IN ALL MACHINES

PS Booster (PSB)

The nominal LHC-type single proton bunch (LHCINDIV) is produced by injecting 1.1 turns from LINAC2 into ring 3 of the PSB. The bunch population at injection in the PSB is of the order of 1.3e12 p/b. Capture losses and controlled longitudinal shaving with the main accelerating system C02 reduce this intensity by more than a factor 10 to obtain the nominal 1.15e11 p/b LHC-type single bunch intensity at extraction of ring 3. Two methods were used to increase the extracted intensity from the PSB: (1) a reduction of the longitudinal shaving right after capture, which enabled to significantly increase the intensity extracted from the PSB, (2) an increase of the number of injected turns from LINAC2, which however generates an increased transverse emittance. Thanks to these methods, the operation team of the PSB can choose to extract a wide range of single bunch intensities (0.05 to 3e11 p/b) with conserved longitudinal emittance and constant transverse emittances. This range can be extended to higher intensities per bunch if the emittance constraints are relaxed.

PS (Proton Synchrotron)

Injecting and accelerating high intensity single bunches in the PS was performed without major issues (a quadrupolar mode damping system suppressed bunch shape oscillations excited at transition energy). When these bunches extracted from the PS were first injected into the SPS in 2010, very high losses and transverse emittance blow-up were observed despite optimization of the orbit, working point, RF voltage and chromaticity ξ. One efficient cure to these issues was blowing up the transverse emittance extracted from the PS (above 2 mm.mrad instead of less than 1.5 mm.mrad, normalised 1σ). This blow-up was first achieved by crudely inserting a screen into the beam in the TT10 transfer line from the PS to the SPS (as seen in Fig. 1). A more controlled blow-up was achieved by missteering the beam already at injection into the PS with the injection kicker KFA45 and septum SMH42. In fact, it appeared that the emittance blow-up in both planes was difficult to control simultaneously and it was then done by sweeping betatron tunes across resonances at injection energy. In 2011, this need to blow-up the beams in the PS disappeared without obvious reason. Finally, following the strong interest to inject smaller emittances in the LHC, a thorough campaign to simultaneously measure transverse emittances in the PSB, PS and SPS was performed and enabled to calibrate the wire scanners across machines to observe where emittance blow-up was generated. This crucial measurement obtained from the beam size and the optics model is however technically complicated and still suffers from repeatability and reliability issues [2].

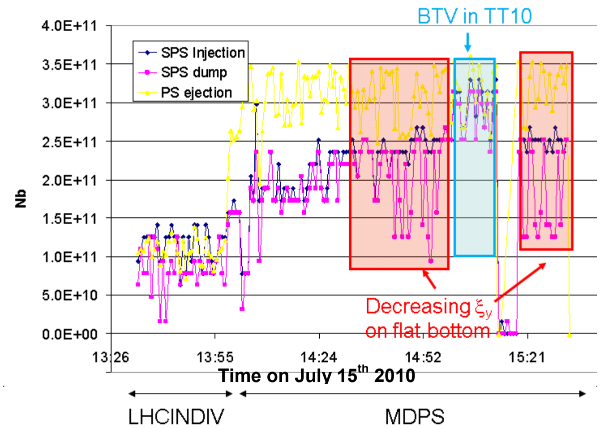

Figure 1: First attempts to inject high intensity single bunches in SPS with the MDPS beam. Compared to the nominal cycle LHCINDIV, intensity at PS ejection (yellow line) is 3 times higher and shows large intensity variation (already present at PSB extraction). Large losses are observed between PS ejection and SPS injection currents (dark blue line), except when the screen was put in TT10 (blue box). Decreasing ξ_y (red boxes) is observed to generate large losses between SPS injection and the end of SPS flat bottom (magenta line).

SPS (Super Proton Synchrotron)

Contrary to the PSB and PS, the injection and acceleration of high intensity single bunches in the SPS required significant tuning besides the usual correction of the transverse oscillations, orbit, working point, energy error, RF phase and capture voltage at injection. Indeed, clear bottlenecks were observed with the nominal gamma transition optics, for which the integer part of the horizontal and vertical tunes $Q_{x,y}$ is equal to 26.

LONGITUDINAL PLANE IN THE SPS

A slow longitudinal instability was observed when the single bunch intensity exceeds 1.9e11 p/b. The 800 MHz RF system was then turned on to increase the synchrotron frequency spread but the bunch was more unstable longitudinally. The 800 MHz RF system was noticed to be already needed to damp synchrotron oscillations of a single bunch with nominal intensity (1.15e11 p/b). Transverse position and bunch shape measurements are then perturbed by this longitudinal instability.

TRANSVERSE PLANE IN THE SPS

Chromaticity Settings

As seen in Figs. 1 and 2, large losses at injection were observed on the SPS flat bottom if the vertical chromaticity was not significantly increased at injection. It is important to note that the first measurement point of the SPS beam current transformer (BCT) is the result of beam current integration over the first 9 ms (i.e. the first 400 turns). As a consequence, fast losses that significantly reduce the bunch intensity in 100 to 200 turns cannot be easily observed if the SPS BCT is not compared to the PS BCT measurement at extraction (as in Fig. 1). Besides, the BCT measures the total intensity, including longitudinally uncaptured beam. Crosschecks with the Fast BCT or the integrated Wall Current Monitor (WCM) signals are therefore needed to assess fast losses, in particular when the beam is not accelerated.

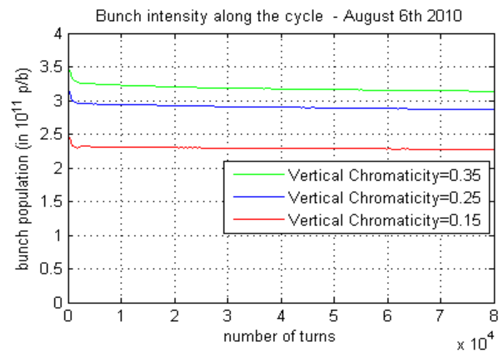

Figure 2: SPS BCT intensity data as a function of vertical chromaticity. The extracted PS intensity was between 3.4 and 3.6e11 p/b in the three displayed cycles.

Transverse Mode Coupling Instability (TMCI)

Together with the Electron cloud instability, TMCI is one of the expected intensity limits in the SPS [3]. Before 2010, the injected bunch intensity did not allow finding the TMCI threshold for the SPS nominal longitudinal emittance at injection (0.35 eVs) and studies have been performed with a lower longitudinal emittance (0.15 eVs) [4-6]. Since the bunch intensity injected from the PS exceeded 3e11 p/b in 2010, a fast vertical instability threshold has been observed with the nominal longitudinal emittance by (1) keeping high vertical chromaticity at injection and decreasing it abruptly along flat bottom after filamentation as shown in Fig. 3, (2) carefully setting chromaticity to a positive value as close as possible to ξ_y=0 at injection and observe the intensity for which the incoming bunch gets unstable (see Fig.4).

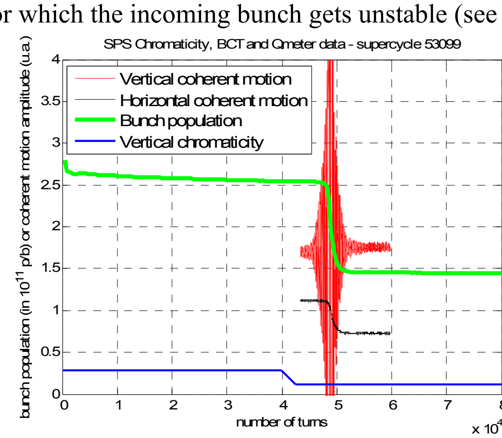

Figure 3: Reducing the vertical chromaticity (blue) in the middle of the SPS flat bottom generated a vertical instability (red) and correlated 40% beam losses (green).

In this case the vertical chromaticity was set to ξ_y=0.05 and 20% losses occurred within the first 100 turns before stabilizing. Head-tail instabilities (mode 0) occur when chromaticity is negative and most of the bunch is then lost. These observations are therefore a strong indication of TMCI. The smallest intensity for which these losses were observed was 1.6e11 p/b, which is now referred to as the TMCI threshold for nominal bunch in the SPS. HEADTAIL simulations without space charge predict TMCI at 1.5e11 p/b, despite a 35% smaller simulated vertical tune shift compared to measurements [7].

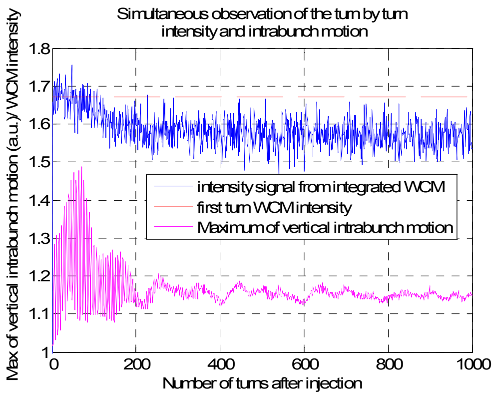

Figure 4: Simultaneous measurements of losses at injection with the WCM (blue) and the maximum of the directional coupler BPW intrabunch vertical motion (magenta). The losses occur when the vertical motion reaches its maximum, indicating a fast transverse instability.

Transverse Emittance Achieved at SPS Flat Top

A measurement campaign to evaluate the achievable vertical emittance and losses as a function of extracted SPS bunch intensity is summarized in Fig. 5 for a long cycle with acceleration (LHCMD1). The end of flat bottom vertical emittance remains constant with small losses for intensities up to 1.5e11 p/b. Beyond 1.5e11 p/b, emittance and losses increase, but above 2.8e11 p/b, losses and emittance blow-up become unbearable.

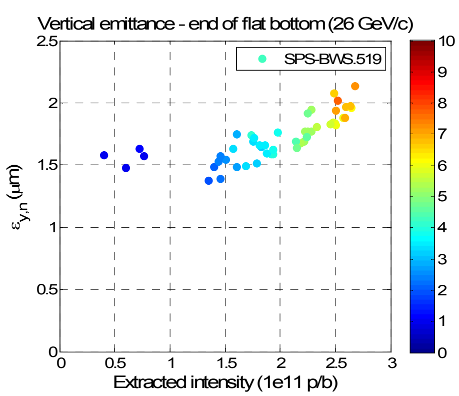

Figure 5: Vertical emittance (norm. 1σ) at the end of the 10 s flat bottom and losses as a function of extracted intensity.

During an LHC beam-beam machine development (MD), it was also possible to assess the effect of chromaticity on the achievable extracted emittance and bunch current for a limited range of intensities, and it turned out that high chromaticity was needed to extract more than 2.7e11, at the expense of a blown up vertical emittance (see Fig. 6).

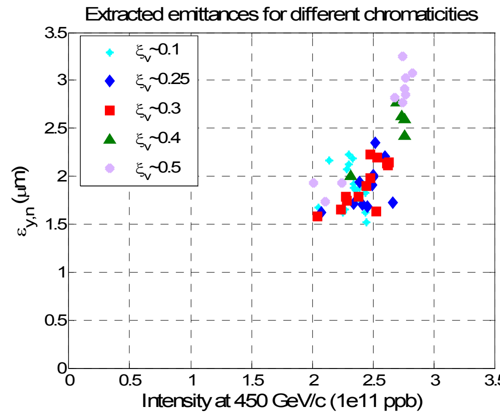

Figure 6: Vertical emittance at SPS extraction (norm. 1σ) and overall losses as a function of extracted intensity with a long SPS cycle and impact of vertical chromaticity.

CONCLUSION

Single bunches with intensities and transverse emittances well beyond ultimate parameters were accelerated up to SPS flat top and injected into the LHC for an MD. Contrary to the low gamma transition optics [8,9], the nominal optics appears to need high chromaticity to keep single bunch losses and transverse emittances low. Higher chromaticity is usually required to damp multibunch effects, and the needed chromaticity for high intensity multibunch beams may be too high to be operational. The TMCI threshold for the nominal SPS bunch with very small (but positive) chromaticity was found to be at 1.6e11 p/b, in good agreement with previous simulations. Among the next steps, the influence of space charge on the simulated TMCI threshold and the working point optimisation to reduce the observed transverse emittance blow-up will be studied.

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