

EXPERIMENTAL STUDIES WITH LOW TRANSITION ENERGY OPTICS IN THE SPS

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Abstract

The optics of the SPS can be tuned to lower transition energy such that the slippage factor at injection is raised by a factor of almost 3. From theory, an increase of the intensity thresholds for transverse mode coupling, longitudinal coupled bunch and longitudinal instabilities due to the loss of Landau damping can be expected. In this paper, experimental studies in the SPS with single bunches of protons with intensities of up to 3.5×10^{11} p/b on the flat bottom and at 450 GeV/c are presented. Longitudinal instabilities were studied with LHC-type beams with 50 ns spacing and injected intensities up to 1.8×10^{11} p/b. The measurements address the increase of intensity thresholds and the achievable transverse emittances in the new low gamma transition optics with respect to the nominal SPS optics. The obtained results are compared with numerical simulations.

INTRODUCTION

Intensity limitations of LHC-type beams in the SPS are being studied since many years now [1]. One of the main limitations for proton beams with the nominal 25 ns bunch spacing is due to electron cloud build-up, which is causing single bunch instability in the vertical plane and transverse emittance blow-up. In the longitudinal plane, single bunch instability, loss of Landau damping and coupled bunch instabilities are observed. Therefore, controlled longitudinal emittance blow-up is performed during the acceleration of LHC beams and a Landau cavity in bunch shortening mode is needed for stabilizing the beam in routine operation [2]. A fast instability in the vertical plane observed with low chromaticity at the injection of LHC-type proton bunches was identified as transverse mode coupling (TMC) [3]. This instability can be mitigated by increasing the vertical chromaticity at the expense of reduced beam quality, i.e. transverse emittance blow up and slow losses.

Under the assumption of constant longitudinal bunch parameters and a matched RF-voltage, increased intensity thresholds for all of the above instabilities can be expected for a higher slippage factor η , as the faster synchrotron motion is damping coherent oscillations. Possible changes of the optics in the SPS for reducing the transition energy were therefore investigated in the framework of the SPS upgrade study team in 2010. A new machine optics was found [4], where the decrease of the integer tunes by 6 units provides a significant increase of the slippage factor. As no hardware modifications are required for this solution, machine study cycles with this new optics have been generated and successfully tested soon after.

05 Beam Dynamics and Electromagnetic Fields

D05 Instabilities - Processes, Impedances, Countermeasures

TRANSVERSE ASPECTS

According to theory, the threshold intensity N_{th} for the transverse mode coupling instability (TMCI) scales like $N_{th} \propto \eta \epsilon / \beta_y$. As η is increasing along the ramp (no transition crossing), injection is the most critical part in the cycle concerning TMCI. The TMCI threshold in the nominal SPS optics (Q26) with chromaticity close to zero and nominal longitudinal parameters was found at 1.6×10^{11} p/b [5], in close agreement with numerical simulations. In the low γ_t optics (Q20), η is increased by a factor 2.85 at injection and the average β -functions are increased by 30% due to the smaller betatron tunes. The TMCI threshold in the Q20 optics can thus be estimated at 3.5×10^{11} p/b. Numerical simulations predict the threshold at 3.2×10^{11} p/b. Figure 1 shows the corresponding bunch mode diagram. The slightly smaller threshold in the simulation can be explained by the higher β -functions at the individual locations of the main SPS impedance sources, such as the MKE kickers.

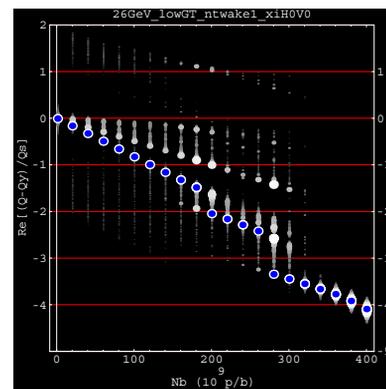


Figure 1: Bunch mode spectrum for the low γ_t optics obtained from the output of HEADTAIL simulations. All presently known impedance sources are included in the SPS impedance model. For each simulated bunch intensity, the blue dot indicates the dominant vertical mode.

Beam stability at injection with the Q20 optics was studied for single bunches with intensities up to 3.8×10^{11} p/b and longitudinal parameters similar to LHC production beams. However, no clear indication for TMCI could be identified up to now. In particular, with vertical chromaticity very close to zero no travelling wave pattern could be observed on the head-tail monitor. Furthermore, losses observed at injection were slow compared to the synchrotron tune and could not be reduced with higher chromaticity. It is not clear up to now, why the TMCI is not observed in the new

optics. A possible reason could be the larger longitudinal emittance of the injected bunches with higher intensities. Another could be damping due to non-linearities present in the real machine but not accounted for in the simulations, for example amplitude detuning, higher order chromaticity, space charge.

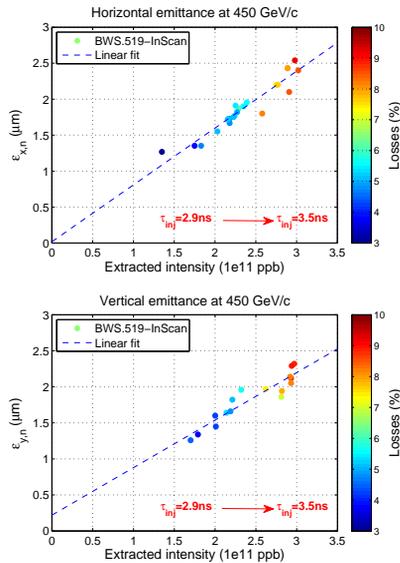


Figure 2: Transverse emittances in the SPS with the low γ_t optics as function of the intensity at top energy. The color code indicates the total losses along the cycle. Note that the injected bunch length was increasing for higher intensity.

The achievable transverse emittances as a function of beam intensity at the end of the LHC injector chain is an important aspect for future LHC upgrades. In dedicated measurements, single bunches with optimized brightness and varying intensity were prepared in the PSB such that the transverse emittances $\varepsilon_{x,n}, \varepsilon_{y,n} \sim 1-1.5 \mu\text{m}$ for intensities up to 3.5×10^{11} p/b. In order to account for potential emittance growth along the flat bottom in the SPS, a long cycle suited for the injection of up to 4 batches of LHC-type bunch trains was used during this study. The emittances measured at top energy are shown in Fig. 2 as a function of the intensity at the end of the cycle, where the color-code indicates the total losses along the cycle extracted from the SPS DC-BCT. The major part of these losses are injection and capture losses, while the rest are continuous losses along the flat bottom. During the experiment the coherent tune shift due to varying intensity was corrected for keeping the working point around $(Q_x, Q_y) \approx (20.13, 20.18)$. Note that the fractional tunes are the same as in the nominal SPS optics for direct comparison. The linear dependence of emittance on the intensity may be attributed to space charge. On the other hand, later studies on a flat bottom cycle indicate that the bunches with high intensity have already larger emittances at extraction from the PS. In all cases, chromaticity was corrected to about $\xi \sim 0.1$. In related studies [5] with the nominal optics, higher chromatic-

ity was needed for avoiding TMCI at injection. However, emittances as low as with the Q20 optics can also be obtained with the Q26 optics with low chromaticity, if higher losses beyond 20% can be tolerated, as was the case for the acceleration of single bunches in the SPS during MD studies [5]. It should be emphasized that all these single bunch studies represent lower bounds on the beam brightness potential which may not be achievable in multi bunch operation due to other limitations.

LONGITUDINAL ASPECTS

For the nominal optics, the longitudinal coupled bunch instability has a very low threshold which is decreasing with energy. The minimum threshold, reached on flat top, is proportional to η and is expected to be higher for lower γ_t . On the other hand, for a given longitudinal emittance, the RF voltage needs to be increased $\propto \eta$ in order to obtain the same bunch length at extraction. This could become a limitation for the beam transfer to the 2.5 ns bucket of the LHC, as already now the maximum available voltage of the SPS 200 MHz RF system (7.5 MV) is used in the nominal cycle. Figure 3 shows the RF voltage programs used for measurements in 2011 comparing the longitudinal parameters of the 50 ns LHC beam with 1-4 batches in the nominal and the low γ_t cycle. Both are based on a constant bucket area (0.6 eVs) along the SPS magnetic cycle (dashed lines). As the nominal optics is in use since quite some time, the cycle has been optimized for loss reduction and controlled emittance blow-up. For better comparison, similar adjustments have been made in the low γ_t cycle. The same mismatch at injection is achieved by raising the voltage on the flat bottom in the Q20 optics to 5.6 MV.

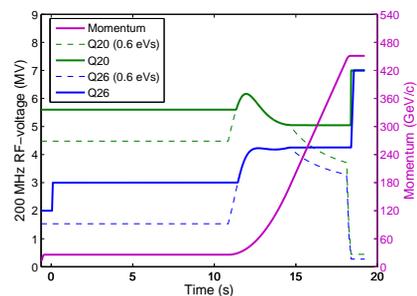


Figure 3: The 200 MHz RF voltage programs used during the measurements together with the magnetic cycle.

Typical examples of the measured bunch length variation along the cycle are presented in Fig. 4. The plots on the top correspond to a single batch at nominal intensity ($N_{nom} \sim 1.3 \times 10^{11}$ p/b) without controlled emittance blow-up and using only the 200 MHz RF system. In both cycles the beam becomes unstable during the ramp. As expected [2], the instability appears at higher energy in the low γ_t cycle. Since the longitudinal parameters (emittances, bunch lengths) are similar, the difference in the threshold should come mainly from the difference in η (ratio ~ 1.6). Fig-

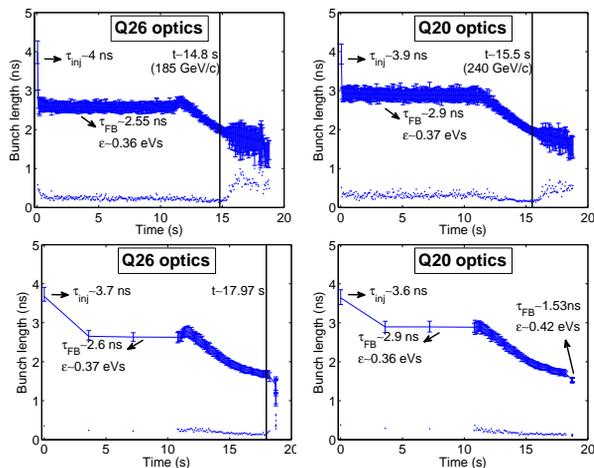


Figure 4: Typical examples of the averaged bunch length variation along the cycle for single LHC batches. Top: nominal intensity ($\sim 1.3 \times 10^{11}$ p/b) in single RF system. Bottom: higher intensity ($\sim 1.6 \times 10^{11}$ p/b at flat top) with double RF system. The bunch length spread inside the batch is shown on the plot bottom. The vertical lines indicate the time of the instability onset.

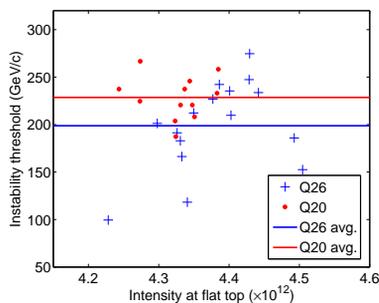


Figure 5: Beam energy at which the instability starts during the ramp versus the intensity at flat top for single batches in the 200 MHz RF system. The horizontal lines represent the corresponding average values.

ure 5 presents intensity thresholds for several acquisitions with similar initial beam conditions. The observed spread of the identified thresholds can be explained by the varying beam parameters at injection. Despite this, the average values clearly indicate a higher threshold in the Q20 cycle.

Better beam stability in both cycles was achieved by switching on the 800 MHz RF system at $V_{800} = V_{200}/10$ in bunch shortening mode. This was sufficient to stabilize the beam in the low γ_t cycle up to $\sim 1.6 \times 10^{11}$ p/b at flat top (1.8×10^{11} p/b injected), where $\tau \sim 1.53$ ns and $\varepsilon \sim 0.42$ eVs. However, in the nominal cycle some bunches were still unstable at flat top ($\tau \sim 1.41$ ns, $\varepsilon \sim 0.46$ eVs), cf. Fig. 4. The controlled emittance blow-up required in the nominal optics can thus be reduced proportionally in the low γ_t cycle. Indeed the threshold for the loss of Landau damping $N_{th} \sim \varepsilon^2 \eta \tau$. Taking into account that the bunch length scales as $\tau \sim (\varepsilon^2 \eta / V)^{1/4}$, a smaller emittance $\varepsilon \sim \eta^{-1/2}$

will be needed for stability in the low γ_t optics. This smaller emittance should then give the same bunch length as with the nominal optics. Further studies are needed, as increased beam losses up to 10% were observed in both cycles at higher intensity ($\sim 1.8 \times 10^{11}$ p/b injected).

Larger controlled emittance blow-up will be needed to stabilize the beam with ultimate LHC intensity N_{ult} in the nominal SPS optics. As the emittance should be increased $\propto \sqrt{N}$, a voltage $N_{ult}/N_{nom} \sim 1.4$ times higher than the present maximum would be required to obtain the same bunch length. It is also possible that, for these high intensities, larger longitudinal emittances are required for stability at 450 GeV in LHC itself. Then the beam transfer to the LHC 400 MHz RF system becomes critical. In addition, the existing 200 MHz RF system in the SPS can provide much less voltage at ultimate LHC current (25 ns spaced beam) due to beam loading. A solution for this problem is to rearrange the existing 4 cavities into 6 cavities of shorter length with 2 extra RF power plants [6].

CONCLUSION AND OUTLOOK

Experimental tests with the new low γ_t optics in the SPS show remarkable results. As expected, clear improvement of beam stability has been observed in single and multi bunch experiments. Future studies will concentrate on beam transfer to LHC and the injection of 25 ns LHC-type bunch trains addressing the critical question of which longitudinal emittance is sufficient for beam stability on the flat top in the low γ_t optics. Finally, experiments will be dedicated to electron cloud effects, as numerical simulations [7] predict a higher threshold for the electron cloud instability in the new optics at injection.

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