# INCREASING INSTABILITY THRESHOLDS IN THE SPS BY LOWERING TRANSITION ENERGY

H. Bartosik, G. Arduini, T. Argyropoulos, T. Bohl, S. Cettour-Cave, K. Cornelis,
J. Esteban Muller, W. Höfle, Y. Papaphilippou, G. Rumolo, B. Salvant, E. Shaposhnikova,
CERN, Geneva, Switzerland

*Abstract*

A new optics for the SPS with lower transition energy was tested experimentally during 2010-2011, showing a significant increase of the single bunch instability thresholds at injection due to the 3-fold increase of the slip factor. The performed machine studies for different LHC beams and intensities are summarized in this paper. In particular, the search for the single bunch TMCI threshold in the new optics is presented. Observations on the longitudinal multi-bunch stability are compared between the nominal and the low-transition optics. Finally, optics variants with higher vertical tunes are discussed, which could allow to further increase the thresholds for TMCI and other vertical instabilities by reducing the vertical beta function.

## INTRODUCTION

Performance limitations of LHC beams in the CERN accelerator complex are presently studied in the frame of the LHC injectors upgrade project (LIU). In the SPS, known intensity limitations are due to beam loading in the RF system and due to various single and multi bunch instabilities [1]. At injection, the transverse beam coupling impedance drives a single bunch transverse mode coupling instability (TMCI) in the vertical plane. Furthermore, single bunches suffer from longitudinal instability during the ramp. This instability is enhanced in the presence of many closely spaced bunches in the machine. In addition to the use of the 800 MHz system as Landau cavity in bunch shortening mode, longitudinal stability of LHC beams requires controlled longitudinal emittance blow-up during the ramp [2]. The performance of future high intensity LHC beams with 25 ns bunch spacing and high brightness is expected to be limited by electron cloud effects in the main dipole magnets leading to transverse emittance blow-up and transverse instabilities.

For constant longitudinal bunch parameters and a matched RF-voltage, higher intensity thresholds for all of the above instabilities can be expected when increasing the slip factor $\eta$. An optics with lower transition energy $\gamma_t$ [3] and thus larger slip factor $\eta$ (LHC beams are injected always above transition in the SPS) is being tested in a series of machine studies [4] since the end of 2010. The lower $\gamma_t$ is thereby achieved by a mere reduction of the betatron tunes by 6 integer units in both planes, exploiting the fact that in a FODO lattice $\gamma_t$ scales like the horizontal phase advance in the arcs. Experimental results with this so-called Q20 optics are presented in the following.

## TRANSVERSE ASPECTS

One of the main motivations for reducing the transition energy in the SPS comes from the single bunch intensity limitation due to the TMCI at injection. The corresponding instability threshold in the nominal SPS optics for LHC beams was predicted in simulations and later confirmed experimentally at around $N_{th} \simeq 1.6 \times 10^{11}$ p/b [5], when injecting single bunches with a longitudinal emittance of $\varepsilon_l \simeq 0.35$ eVs and the machine tuned to small positive vertical chromaticity $\xi_y$. The transition energy in the Q20 optics is reduced to $\gamma_t = 18$ compared to $\gamma_t = 22.8$ in the nominal optics, which corresponds to a 2.85 times larger slip factor at injection energy. Since the TMCI instability threshold scales like [6]

$$N_{th} \propto \frac{|\eta|\varepsilon_l}{\beta_y} \tag{1}$$

and the average vertical beta-function $\beta_y$ is roughly 30% larger, the corresponding threshold in the Q20 optics can be estimated at around $3.5 \times 10^{11}$ p/b. In comparison to that, numerical simulations based on a detailed model of the SPS transverse impedance predict the threshold at around $3.2 \times 10^{11}$ p/b. It should be noted that space charge effects are not taken into account in these simulations.

Single bunches with intensities up to $5 \times 10^{11}$ p/b and nominal longitudinal beam parameters were injected into the SPS Q20 optics (present LHC beams have around $1.5 \times 10^{11}$ p/b), without transverse feedback. The voltage of the 200 MHz RF system was set to $V_{200} = 4.5$ MV throughout the flat bottom, while the 800 MHz component was switched off. The intensity of the injected beam was varied by changing the number of turns injected from LINAC2 into ring 3 of the PS Booster. Thus, the transverse emittance was increasing proportional to the intensity, while the longitudinal beam parameters remained constant with a bunch length of around $\tau = 3.9$ ns and longitudinal emittance of $\varepsilon_l = 0.34$ eVs at the exit of the PS.

In order to identify fast losses at injection potentially caused by TMCI, the reading of the SPS dc beam current transformer (BCT) at 100 ms after injection is compared with the PS intensity before extraction. Figure 1 shows their ratio as a function of the PS extracted intensity for different settings of the vertical chromaticity knob QPV. Note that zero vertical chromaticity $\xi_y$ at injection corresponds to QPV=-0.59. For QPV=-0.60 ($\xi_y \approx -0.01$) a head tail instability caused by negative chromaticity was observed, leading to strong losses at around 50 ms after injection or later in the cycle. On the other hand, stable beam

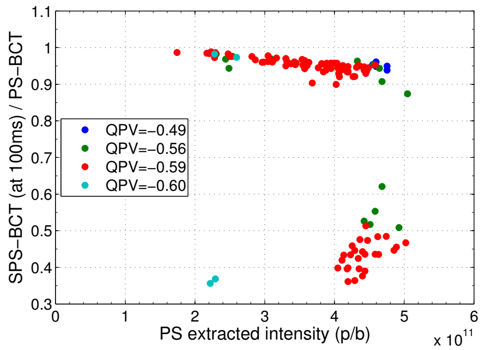


Figure 1: Ratio of the SPS intensity at 100 ms to the PS extracted intensity for different settings of the vertical chromaticity knob QPV.

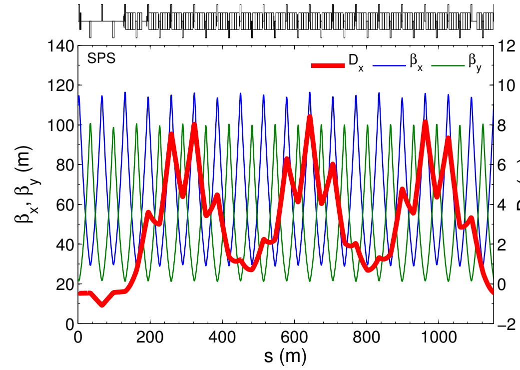


Figure 2: SPS optics with split tunes. Small vertical beta functions are obtained keeping the vertical tune at its nominal value, while the reduced horizontal tune yields low $\gamma_t$.

conditions with chromaticity close to zero were obtained for intensities up to $4 \times 10^{11}$ p/b, at which the (linearly increasing with intensity) losses at injection reach about 5%. The mechanism causing these injection losses remains to be understood. For intensities between $4 \times 10^{11}$ p/b and $5 \times 10^{11}$ p/b fast losses of more than 50% within the first 50 ms after injection were observed for vertical chromaticity close to zero. Stable beam conditions in this intensity range could be re-established with a chromaticity of $\xi_y \geq 0.1$ (QPV $\geq -0.49$). Further studies are needed for clarifying if these observations are associated with a TMCI.

### *Optics Variants*

Compared to the nominal SPS working point for LHC proton beams $(Q_x, Q_y) = (26.13, 26.18)$ in the Q26 optics, the betatron tunes are moved to $(Q_x, Q_y) = (20.13, 20.18)$ in the Q20 optics used for the experimental studies described in this paper. The associated increase of the minimal beta-function values is particularly unfavourable in the vertical plane: a larger beta function at the location of important impedance sources results in a lower instability threshold as shown by Eq. (1). In addition, the aperture of the SPS vacuum chambers is generally smaller in the vertical dimension and thus more critical for round LHC beams. On the other hand, the horizontal aperture is largely sufficient, even for large excursions of the dispersion function.

Since the transition energy in a regular FODO lattice is determined by the horizontal phase advance in the arcs, a low $\gamma_t$ can also be achieved by reducing solely the horizontal tune of the machine. Figure 2 shows the optics functions in one super period of the SPS when it is tuned to $(Q_x, Q_y) = (20.13, 26.18)$. Using these split tunes, the vertical beta-functions remain close to their nominal values, while they are slightly increased in the horizontal plane. The large dispersion in the arcs results then in the desired low transition energy of $\gamma_t = 17.8$. This optics variant will be tested in 2012, potentially further increasing the vertical instability thresholds and the available aperture.

## LONGITUDINAL ASPECTS

For the Q26 optics used for LHC filling, the longitudinal multi bunch instability has a very low intensity threshold, which is decreasing with the beam energy [2]. It was shown in previous studies [4] that the corresponding instability threshold for nominal and ultimate beam intensities is higher in the Q20 optics, due to the larger slip factor.

In routine operation the beam is stabilized by the 800 MHz RF system in bunch shortening mode combined with controlled longitudinal emittance blow-up during the ramp. At flat top the 200 MHz RF system is operated at its maximal voltage of $V_{200} = 7$ MV in order to shorten the bunches for beam transfer to the LHC 400 MHz bucket.

Due to the limited RF voltage, bunches with the same emittance at extraction will be longer in the low $\gamma_t$ optics. On the other hand, less controlled longitudinal emittance blow-up is required compared to the nominal optics for achieving the same beam stability. It can be thus expected that a similar bunch length at flat top can be obtained with stable beams in both optics but with different longitudinal emittances.

Beam stability was studied in the Q20 and the Q26 optics with the same beam conditions, i.e. one batch of 50 ns LHC bunches with $1.6 \times 10^{11}$ p/b at injection without controlled

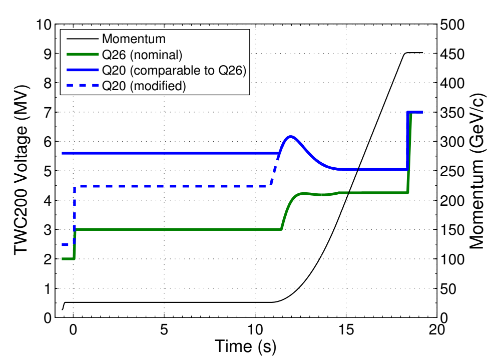


Figure 3: Momentum and 200 MHz voltage program along the cycle for the Q26 and Q20 optics, together with the modifications mentioned in the text.


ISBN 978-3-95450-115-1

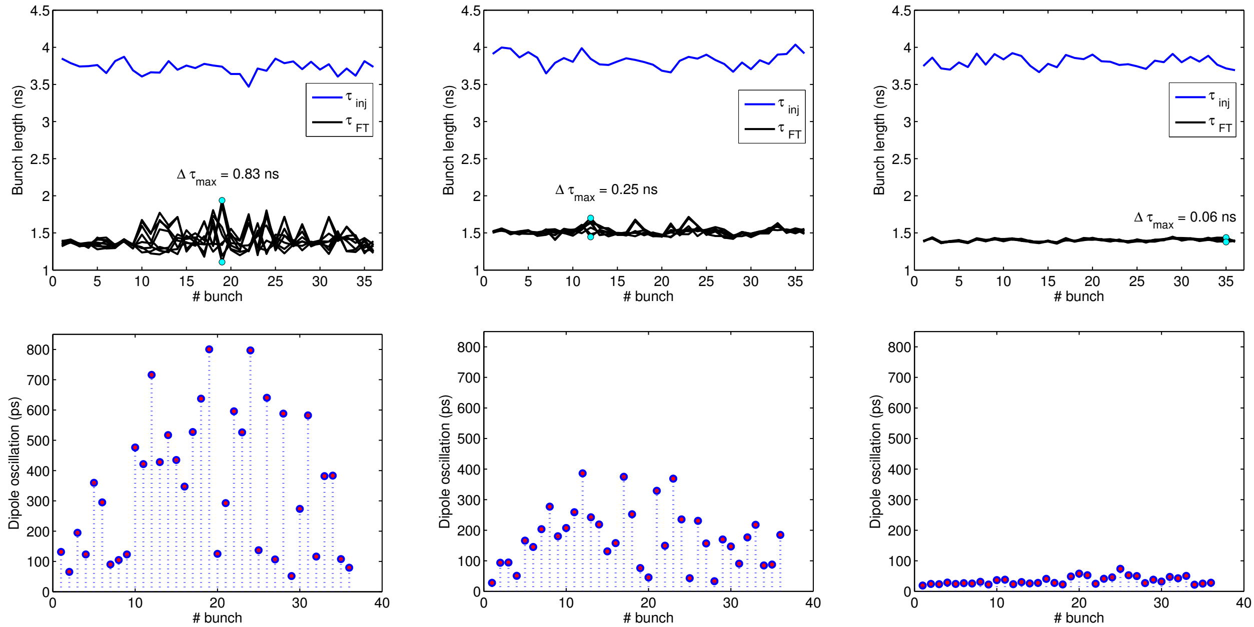


Figure 4: Bunch length (top) and bunch position (bottom) oscillations at flat top for the bunches of single batch 50 ns LHC beam. Columns correspond to Q26 (left), Q20 with comparable RF settings (middle) and Q20 after optimization (right).

longitudinal emittance blow-up. The operational 200 MHz voltage $V_{200}$ was applied in Q26 and the 800 MHz voltage was programmed to $V_{800} = V_{200}/10$. A comparable voltage program scaled to the larger $\eta$ of the Q20 optics was used in the first part of the studies, as shown in Fig. 3.

The stability analysis of the beam is based on the bunch length variation and position oscillations obtained at FT from 8 beam profiles acquired during one synchrotron period, shown in Fig. 4. In the Q26 optics, the beam was unstable with large amplitudes of dipole and quadrupole oscillations. Indeed, controlled longitudinal emittance blow-up to $\epsilon_l \simeq 0.63$ eVs is applied in routine operation for LHC filling, which results then in bunch lengths of about 1.5 ns at extraction. Clearly better stability was observed in the Q20 optics with the comparable voltage program (see Fig. 4), although controlled longitudinal emittance blow-up is still needed for obtaining sufficient beam stability for extraction to the LHC.

The voltage program for the Q20 optics was then optimized to improve the beam stability and at the same time to reduce the particle losses along the cycle. In addition the gain of the longitudinal dampers at the flat bottom was adjusted. The beam was stabilized with the voltage program presented in Fig. 3, where $V_{200}$ is 2.5 MV at injection and 50 ms later is raised to 4.5 MV, providing smaller emittances at flat bottom (0.3 eVs). For this small emittance the beam was stable throughout the cycle without controlled longitudinal emittance blow-up as shown in Fig. 4, where $\epsilon_l \simeq 0.37$ eVs and the mean bunch length around $\tau \simeq 1.4$ ns at flat top. This is compatible with the required parameters for injection to the LHC and would allow also for controlled longitudinal emittance blow-up if needed for stability with higher intensities.

## CONCLUSION AND OUTLOOK

The SPS low-transition energy optics studied since 2010 is observed to eliminate performance limitations due to the single bunch TMCI in the intensity range required by the LHC injectors upgrade project. Concerning longitudinal beam characteristics at extraction, mean bunch lengths comparable to the nominal ones can be achieved in the Q20 optics, since less controlled emittance blow-up is required for beam stability. Further studies planned for this year aim to test extraction from the Q20 optics and injection into LHC, addressing also the question whether the smaller longitudinal emittance can be digested by the LHC.

## ACKNOWLEDGEMENTS

The authors would like to thank all members of OP for their constant support and help during machine studies.

## REFERENCES

[1] E. Shaposhnikova, "Lessons from SPS studies in 2010", Proceedings of Chamonix 2011 workshop on LHC Performance (2011) and references therein.

[2] E. Shaposhnikova, CERN SL-Note-2001-031 HRF (2001).

[3] H. Bartosik, G. Arduini and Y. Papaphilippou, "Optics considerations for lowering transition energy in the SPS", IPAC11 (2011).

[4] H. Bartosik et al., "Experimental studies with low transition energy optics in the SPS", IPAC11 (2011).

[5] B. Salvant et al., "Probing intensity limits of LHC-type bunches in SPS with nominal optics", IPAC11 (2011).

[6] E. Métral et al., "Transverse Mode Coupling Instability in the CERN Super Proton Synchrotron", HB04 (2004).