LOW GAMMA TRANSITION OPTICS FOR THE SPS: SIMULATION AND EXPERIMENTAL RESULTS FOR HIGH BRIGHTNESS BEAMS

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Abstract

The single bunch transverse mode coupling instability (TMCI) at injection is presently one of the main intensity limitation for LHC beams in the SPS. A new optics for the SPS with lower transition energy yields an almost 3-fold increase of the slip factor at injection energy and thus a significantly higher TMCI threshold, as demonstrated both in simulations and in experimental studies. It is observed furthermore that the low gamma transition optics yields better longitudinal stability throughout the entire acceleration cycle. In addition, simulations predict a higher threshold for the electron cloud driven single bunch instability, which might become an important limitation for high intensity LHC beams with the nominal 25 ns bunch spacing. This contribution gives a summary of the experimental and simulation studies, addressing also space charge effects and the achievable brightness with high intensity single bunch beams.

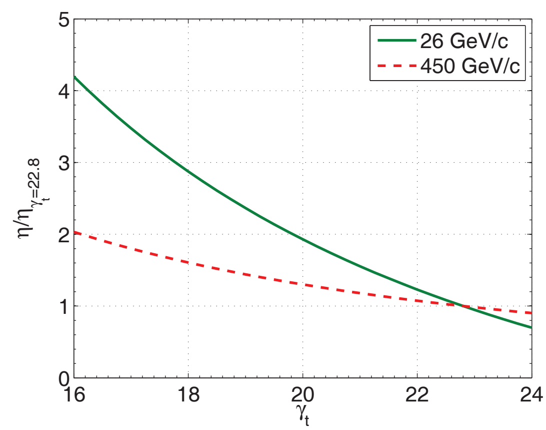

Figure 1: Slip factor η relative to the value of the nominal SPS optics (nominal $\gamma_t = 22.8$) as a function of γ_t. At injection $\gamma = 27.7$ and at extraction $\gamma = 480$.

INTRODUCTION

Performance limitations for LHC beams in the CERN accelerator complex and their mitigations are studied in the frame of the LHC injectors upgrade (LIU) project, with the goal to reach the beam parameters required for the future high luminosity LHC (HL-LHC). Presently known intensity limitations in the SPS are due to beam loading in the travelling wave 200 MHz and 800 MHz cavities, which requires an upgrade of 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. For mitigating longitudinal instabilities, a double harmonic RF system is used for LHC beams where the 800 MHz system serves as Landau cavity in bunch shortening mode. Controlled longitudinal emittance blow-up is performed during the ramp to stabilize the beam at high energies up to the flat top [2]. The performance of future high intensity LHC beams with 25 ns bunch spacing might be furthermore limited by transverse emittance blow-up and transverse instabilities due to electron cloud effects in the main dipole magnets.

For constant longitudinal bunch parameters and a matched RF-voltage, higher intensity thresholds for all of the above instabilities are expected when increasing the slip factor η. The nominal SPS optics has $\gamma_t = 22.8$. Since the working point in this optics is $(Q_x, Q_y) = (26.13, 26.18)$, it will be referred to as "Q26" optics in the following. LHC-type proton beams are injected with $\gamma = 27.7$ (26 GeV/c), i.e. above transition. By reducing γ_t, the slip factor is increased throughout the acceleration cycle with the largest relative gain at injection energy. Figure 1 shows η normalized to the value in the nominal SPS optics ($\eta_{\gamma_t=22.8}$) as function of γ_t for injection energy and for top energy. A significant gain of beam stability can thus be expected for a relatively small reduction of γ_t, especially in the low energy part of the acceleration cycle.

In a FODO lattice (like the SPS) γ_t scales like the horizontal phase advance in the arcs. This is exploited in the "Q20" optics [3], where the working point of the SPS is changed to $(Q_x, Q_y) = (20.13, 20.18)$. As in the nominal optics, the phase advance along the arcs is close to multiples of 2π and thus the dispersion in the straight sections is small. The transition energy is reduced to $\gamma_t = 18$ in the Q20 optics, which translates to a relative gain of η by a factor 2.85 at injection energy and a factor 1.6 at top energy compared to the nominal optics (see Fig. 1). Since the end of 2010, the Q20 optics was successfully tested in a series of machine studies and proved to show the expected gain of beam stability both in the transverse and in the longitudinal plane. An overview of the studies and the present understanding of instabilities in comparison with the nominal SPS optics will be given in the following.

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TRANSVERSE ASPECTS

One of the main motivations for reducing the transition energy in the SPS comes from the single bunch intensity limitation due to a TMCI in the vertical plane at injection. The corresponding instability threshold for small positive vertical chromaticity ξ_y in the nominal SPS optics was predicted in simulations and found experimentally at around $N_{th} \approx 1.6 \times 10^{11}$ p/b [4], when injecting single bunches with a longitudinal emittance of $\varepsilon_l \approx 0.35$ eVs. Since the TMCI threshold scales like [5]

$$N_{th} \propto \frac{|\eta|\varepsilon_l}{\beta_y} \quad (1)$$

the corresponding threshold in the Q20 optics at injection energy can be estimated at around 3.5×10^{11} p/b, since η is 2.85 times higher with respect to the nominal optics and it can be assumed that the vertical beta-function β_y at the location of important impedance sources is 30% larger (equivalent to the average increase of the beta functions). It should be emphasized here that space charge effects are not taken into account in this model.

High intensity single bunches were injected with a longitudinal emittance close to the nominal $\varepsilon_l = 0.35$ eVs at the exit of the PS, without using the 800 MHz cavity and without transverse damper in the SPS. No instability was observed up to intensities of $N_b \approx 4 \times 10^{11}$ p/b [6]. Beyond this intensity a vertical instability caused losses of up to 50% within the first 100 ms after injection, which was suppressed by slightly increasing the vertical chromaticity. Similar studies were performed recently, this time with smaller longitudinal emittance at PS extraction ($\varepsilon_l = 0.32$ eVs) and a reduced RF voltage of $V_{200} = 3$ MV in the SPS. Furthermore the injection time within the cycle was delayed by one basic period (1.2 s) in order to minimize transient effects of eddy currents on the chromaticity. As the chromaticity has non-negligible nonlinear components, a scan of the vertical (linear) chromaticity knob QPV for different intensities was performed. Note that the QPV knob (controlling $\xi_y = Q'_y/Q_y$) has a large negative offset since more than half of the natural vertical chromaticity is compensated by the sextupole components of the dipoles. For negative chromaticity and low intensity the expected headtail mode 0 instability was observed. This instability was clearly identified up to QPV=-0.57. Figure 2 shows the measured vertical tune Q_y as a function of intensity for different chromaticity settings. For QPV=-0.55, the beam was stable in some cases but in other cases became unstable with losses of up to 80% within the first 100 ms. No instability was observed for QPV$\geq$-0.53. While HEADTAIL simulations with the SPS impedance model predict coupling between higher order modes [7], the measured tunes follow a straight line in all cases (i.e. stable and unstable), which is thus compatible with the observation of a headtail mode 0 instability for QPV≤ -0.55. Indeed, as shown in Fig. 3 the instability observed for high intensity with QPV=-0.55 is slow compared to the synchrotron tune

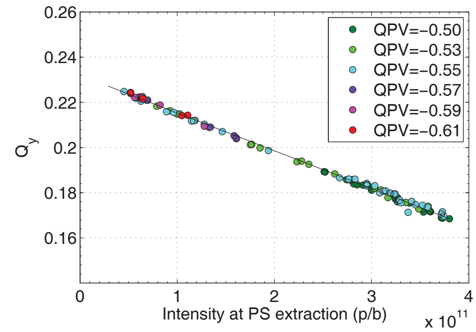

Figure 2: Vertical tune as function of intensity at PS extraction for different settings of the vertical chromaticity knob.

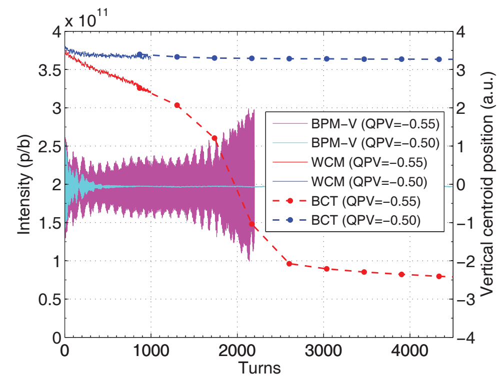

Figure 3: The intensity obtained from the wall current monitor (WCM) and the beam current transformer (BCT) are shown together with the vertical centroid position for two different settings for vertical chromaticity. Losses close to injection are due to injection oscillations.

($1/Q_s \approx 100$ turns). However it should not be forgotten that space charge effects can modify the mode spectrum. Further studies and measurements of the intra bunch motion are needed for drawing final conclusions.

A series of measurements were performed in order to assess brightness limitations in the SPS. Figure 4 shows the vertical emittance at SPS flat top of a long LHC-type cycle (10.86 s flat bottom) as a function of intensity for single bunches for both optics. As indicated by the color code, moderate losses linearly increasing with intensity are observed in the Q20 optics with low vertical chromaticity ($\xi_y \approx 0.1$). Note that the working point was corrected for intensity detuning and adjusted to $(Q_x, Q_y) = (20.13, 20.18)$. The space charge tune spread for the measured beam parameters can be estimated as $(\Delta Q_x, \Delta Q_y) \approx (-0.12, -0.18)$. An equivalent measurement was performed using the Q26 nominal optics. In this case however, the vertical chromaticity had to be increased ($\xi_y \approx 0.25$) in order to mitigate fast losses at injection. The total losses along the cycle (dominated by losses at injection) reach up to 20% when injecting $N_b = 3 \times 10^{11}$ p/b. Higher vertical chromaticity reduces losses at injection but results in higher losses on the long flat bottom and does

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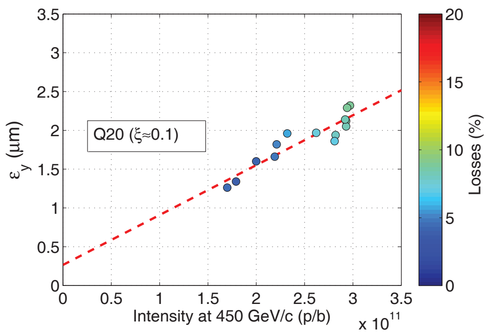

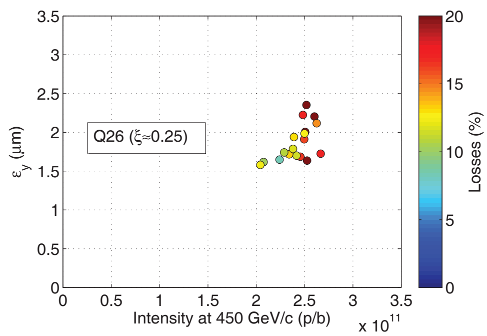

Figure 4: Vertical emittance measured at SPS flat top as function of the intensity for the Q20 optics (top) and the nominal SPS optics Q26 (bottom).

not improve the overall transmission. Thus the Q20 optics clearly increases the intensity and brightness reach for LHC type single bunches even with small chromaticity. For accommodating larger space charge tune spreads, working points for the Q20 optics with increased fractional tunes are being studied [8].

ELECTRON CLOUD INSTABILITY

During the first machine studies with LHC type beams with the nominal 25 ns bunch spacing in the early years of 2000, strong electron cloud effects were observed in the SPS. Pressure rise, fast losses at injection and emittance growth along the bunch train were limiting the machine performance. After a series of scrubbing runs and machine studies with 25 ns beams in the following years, the secondary electron yield of the SPS vacuum chambers was significantly reduced and presently the nominal LHC beam can be produced within design specifications. Significantly higher intensities will be required for the HL-LHC project and it is not clear yet if electron cloud effects will become a limitation in the future.

Since the electron cloud instability (ECI) threshold scales with the synchrotron tune Q_s a clear benefit from the larger η in the Q20 optics is expected. A series of numerical simulations were performed [9] using the HEADTAIL code. Figure 5 shows the expected threshold electron density ρ_c for the fast vertical instability in the nominal and the Q20 optics as a function of the bunch intensity N_b at injection energy for matched RF voltages. It was assumed here that the electrons are confined in bending magnets (where the lowest threshold for the electron cloud build-up in the machine is expected) with a uniform transverse distribution before the bunch passage. Clearly higher ECI thresholds are predicted for the Q20 optics.

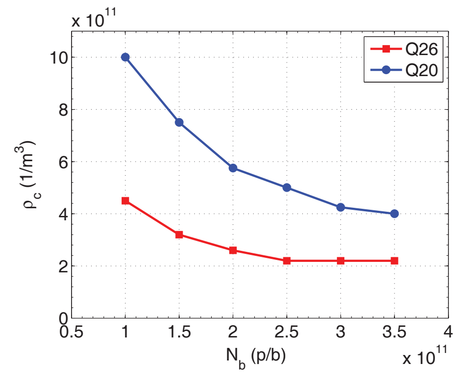

Figure 5: Threshold electron density ρ_c as function of the bunch intensity N_b for the nominal and the Q20 optics as obtained with HEADTAIL for injection energy.

LONGITUDINAL ASPECTS

In the Q26 nominal SPS optics the longitudinal multi-bunch instability has a very low intensity threshold, which is decreasing with the beam energy. It is expected that for RF voltage programs providing similar beam parameters (emittances, bunch lengths) the corresponding instability threshold is higher in the Q20 optics. Figure 6 presents the calculated narrow band impedance thresholds along the cycle for both optics in the 200 MHz single RF system for a longitudinal emittance of $\varepsilon_l = 0.5$ eVs and the corresponding voltage programs. For better comparison a constant filling factor $q_p = 0.9$ (in momentum) is chosen. Note that the impedance threshold reaches its minimal value at flat top for both optics. Controlled longitudinal emittance blow-up during the ramp in combination with the use of a double harmonic RF system (800 MHz) in bunch shortening mode are used in routine operation to stabilize the beam longitudinally in the high energy part of the cycle.

On the flat bottom the estimated threshold impedance with the Q20 optics is a factor 2.85 times higher compared to the nominal optics (see Fig. 6). This provides a significant margin for increasing the intensity with the Q20 optics, while in the nominal optics the currently operational 50 ns LHC beam with an intensity of $N_b \approx 1.8 \times 10^{11}$ p/b is at the limit of stability on the injection plateau. This longitudinal instability on flat bottom of the Q26 optics was addressed in single bunch measurements using only the single harmonic 200 MHz RF system. Figure 7 shows that the instability on flat bottom strongly depends on the capture voltage [10]. Single bunches ($N_b \approx 1.1 \times 10^{11}$ p/b) injected into $V_{200} = 3$ MV become very unstable (same for 2 MV). This effect is enhanced by the specific particle distribution coming from the PS after bunch rotation [11]. Fig-

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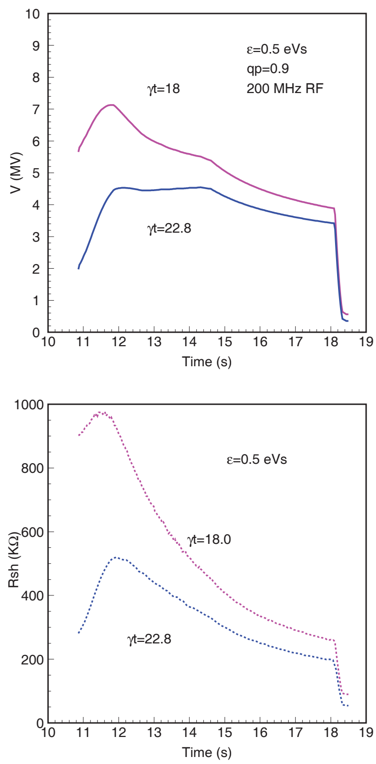

Figure 6: Voltage programs (top) and narrow-band impedance thresholds (bottom) through the cycle for Q26 (blue curve) and Q20 (magenta curve) optics in a single RF system for longitudinal emittance $\varepsilon_l = 0.5$ eVs. Acceleration starts at 10.86 s.

ure 7 shows that stable beam conditions are obtained with a capture voltage of 1 MV. Although this voltage setting is closer to the matched voltage for the PS to SPS transfer, this setting cannot be used in operation with the multi-bunch LHC beams due to residual beam loading. In fact, measurements of the 50 ns beam with $N_b \approx 1.7 \times 10^{11}$ p/b show that regarding the particle losses the voltage at injection should not be reduced below 1.8 MV. Moreover, optimal beam conditions for all four batches require an even higher voltage of 3 MV constant at flat bottom. In the Q20 optics on the other hand, the required voltage for the same longitudinal parameters is higher due to the larger $|\eta|$. This makes the effect of beam loading less critical. A voltage setting closer to the matched conditions can be used, which reduces drastically the initial perturbation of the longitudinal phase space distribution. Indeed, for the 50 ns LHC beam with $N_b \approx 1.7 \times 10^{11}$ p/b a total transmission of around 95% can be achieved when injecting into 3 MV in the Q20 optics. The corresponding voltage setting for the Q26 optics of about 1 MV results in 50% beam losses.

To stabilize the beam at flat top in routine operation with the Q26 optics, controlled longitudinal emittance blow-up is performed 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 bunch length for beam transfer to

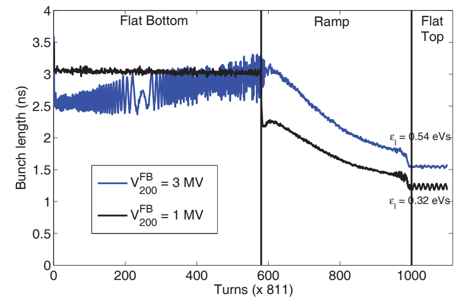

Figure 7: Bunch length evolution along the cycle for single bunches ($N_b \approx 1.1 \times 10^{11}$ p/b) in Q26 with single RF system for two different capture voltages. The voltage programs after the flat bottom are the same in both cases.

the LHC 400 MHz bucket. Due to the limited RF voltage at flat top, bunches with the same longitudinal emittance at extraction will be longer in the low γ_t Q20 optics as the required RF-voltage for the same longitudinal bunch parameters needs to be increased proportional to η (for a stationary bucket). However, the longitudinal instability threshold at flat top (450 GeV/c) is about 50% higher in the Q20 optics and therefore less or no controlled longitudinal emittance blow-up is required compared to the nominal optics for achieving the same beam stability.

Beam stability on flat top was studied in the Q20 and the Q26 optics with the same beam conditions, i.e. one batch of 50 ns LHC bunches with $N_b \approx 1.6 \times 10^{11}$ p/b at injection without controlled longitudinal emittance blow-up. The operational 200 MHz voltage V_{200} was applied in Q26 ($V_{200} = 2$ MV at injection and $V_{200} = 3$ MV on flat bottom) and the 800 MHz voltage was programmed to $V_{800} = V_{200}/10$. The voltage program for the 200 MHz RF system in the Q20 optics was optimized [6] to maximze transmission and beam stability by setting $V_{200} = 2.5$ MV

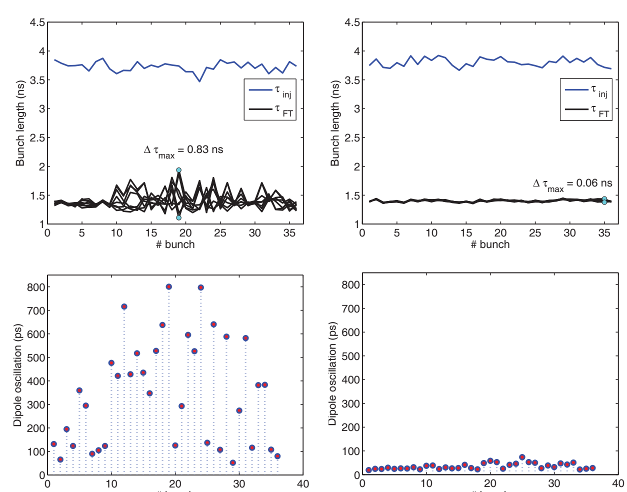

Figure 8: Bunch length (top) and bunch position (bottom) oscillations at flat top for the bunches of a single batch 50 ns LHC beam, for Q26 (left) and for Q20 (right).

at injection and 4.5 MV on the flat bottom and the voltage for the 800 MHz cavity to roughly $V_{800} = V_{200}/10$. This voltage program provides smaller longitudinal emittances at flat bottom (0.3 eVs). For this small emittance the beam was stable throughout the cycle without controlled longitudinal emittance blow-up. Figure 8 shows a comparison of the beam stability between the two optics, where for the Q20 the longitudinal emittance $\epsilon_l \approx 0.37$ eVs and the mean bunch length around $\tau \approx 1.4$ ns at flat top. Note that this bunch length is compatible with injection into the 400 MHz system of the LHC and would allow also for controlled longitudinal emittance blow-up if needed for stability with higher intensities. As will be shown in the following, similar bunch length can thus be achieved in both optics for the same longitudinal stability at flat top, but with smaller longitudinal emittance for the Q20 optics.

An MD study was dedicated to test the extraction from the Q20 optics and the injection of the 50 ns beam with $N_b \approx 1.58 \times 10^{11}$ p/b (at SPS flat top) into the LHC. One LHC fill was performed without controlled emittance blow-up in the SPS so that $\varepsilon_l \approx 0.37$ eVs. The bunch length distribution at flat top before extraction for this case is shown in Fig. 9 (left) in comparison with the Q26 optics (right) for the same intensity on the same day (with longitudinal blow-up). Note that the mean bunch length is similar in both cases. Although the standard deviation of the bunch length distribution is slightly smaller in Q20, the total spread is comparable for both optics since in some cases individual bunches were slightly unstable in the Q20 optics (the intensity on flat top was slightly higher than in Fig. 8). The impact of the smaller longitudinal emittance on intra beam scattering effects on the LHC flat bottom need to be addressed in further studies. A second fill of the LHC with the Q20 optics was then performed with longitudinal emittance blow-up so that $\varepsilon_l \approx 0.5$ eVs (similar to present operation with Q26) and the bunch length $\tau \approx 1.7$ ns. In this case no increase of the capture losses were observed at LHC injection compared to the previous fill, which therefore would allow for choosing the best setting for controlled longitudinal emittance and bunch length on SPS flat top with the Q20 optics for optimizing the LHC performance.

Since the observation of beam quality issues due to longitudinal instabilities on the SPS flat bottom with the operational LHC beam, it was decided to try the Q20 optics in routine operation. Final preparations for switching to the Q20 optics for the operational LHC proton beams in the SPS are presently ongoing.

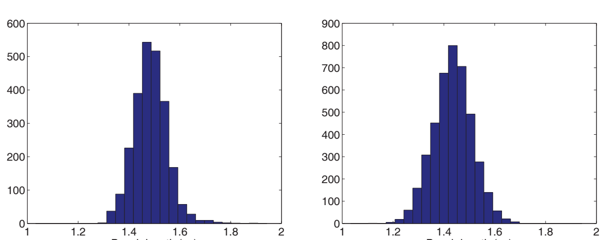

Figure 9: Bunch length distribution on the flat top before extraction for the Q20 optics (left) and the Q26 optics (right) for the 50 ns LHC beam with $N_b \approx 1.58 \times 10^{11}$ p/b.

CONCLUSION AND OUTLOOK

The Q20 SPS low γ_t 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. Numerical simulations predict an increase of the threshold electron density for the onset of the electron cloud instability by roughly a factor 2 on the flat bottom. A nearly threefold increase of the longitudinal narrow band impedance threshold is obtained on flat bottom, while the operational LHC 50 ns beam is close to the instability limit in the Q26 nominal SPS optics. The higher longitudinal instability threshold in the Q20 optics compensates for the limited RF-voltage on flat top, so that similar bunch lengths at extraction can be achieved in both optics but with smaller longitudinal emittance in Q20. Preparations for switching to the Q20 optics in routine operation for LHC filling are presently ongoing.

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