OPTICS CONSIDERATIONS FOR LOWERING TRANSITION ENERGY IN THE SPS

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Abstract

Beam stability for high intensity LHC beams in the SPS can be improved by increasing the slippage factor, i.e. reducing the transition energy. In this paper, possible ways of modifying the optics of the SPS for lower transition energy are reviewed. In particular, a threefold increase of the slippage factor at injection can be achieved by decreasing the integer part of the tunes by 6 units. The properties of this new low-transition optics are compared with the nominal SPS optics, including working point and resonance behavior. Possible limitations are discussed.

INTRODUCTION

Instabilities in the CERN SPS are presently one of the main performance limitations of the entire LHC injector chain [1]. Most prominent for LHC-type beams with the nominal 25 ns spacing is the vertical fast instability and transverse emittance blow-up caused by the electron cloud, which is formed in the presence of many bunches in the machine. The main intensity limitation for single bunches has been identified as the transverse mode coupling instability (TMCI) at injection. In the longitudinal plane, indications for loss of Landau damping were observed with LHC bunch trains of nominal intensity with small injected emittance. In addition to single bunch instabilities, a very low threshold is found for the longitudinal coupled bunch instability. Controlled longitudinal emittance blow-up and a Landau cavity in bunch shortening mode are needed for stabilizing the beam. Note that these instability thresholds scale proportional to the slippage factor (assuming constant longitudinal bunch parameters).

The slippage factor is a function of the beam energy (γ) and the transition energy (γ_t) given by

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}. \tag{1}$$

In the case of the nominal SPS optics $\gamma_t = 22.8$. LHC-type proton beams are injected with $\gamma = 27.7$ (26 GeV/c), i.e. above transition. By reducing γ_t, the slippage 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 ($\eta_{\mathrm{nom.}}$) as function of γ_t for injection energy and for top energy. Therefore, significant gain of beam stability can be expected for a relatively small reduction of γ_t, especially in the low energy part of the acceleration cycle.

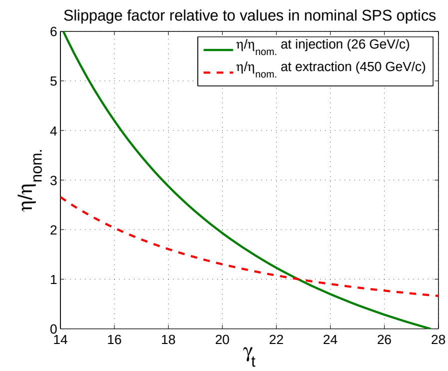

Figure 1: Slippage factor η relative to the value of the nominal optics (nominal $\gamma_t = 22.8$) as a function of γ_t. At injection $\gamma = 27.7$ and at extraction $\gamma = 480$.

REDUCING SPS TRANSITION ENERGY

The SPS has a super-symmetry of 6 with a regular FODO lattice built of 108 cells, 16 per arc and 2 per long straight section. In the nominal SPS optics, the phase advance per cell is close to $\pi/2$, resulting in betatron tunes between 26 and 27. Low dispersion in the long straight sections is achieved by a missing dipole scheme in the adjacent arc cells. Figure 2 shows the optics functions in the SPS lattice for the nominal optics.

The transition energy (γ_t) is defined through the integral of the dispersion function $D_x(s)$ in regions with finite bending radius $\rho(s)$, i.e. in the bending magnets,

$$\frac{1}{\gamma_t^2} = \frac{1}{C}\oint \frac{D_x(s)}{\rho(s)} ds. \tag{2}$$

As a reduction of γ_t is achieved by increasing $D_x(s)$ in the dipoles, past proposals considered the installation of additional quadrupoles separated by odd multiples of π for inducing dispersion waves in the arcs [2].

In 2010, a series of alternative solutions for modifying γ_t of the SPS were investigated [3]. The most elegant and promising approach is based on the fact that in a regular FODO lattice, the transition energy scales with the horizontal tune Q_x, i.e. $\gamma_t \propto Q_x$, as shown for the SPS in Fig. 3. Note the asymptotic behavior of γ_t for tunes close to multiples of the super periodicity of the machine, i.e. when the phase advance per super period is a multiple of 2π. This was exploited during a machine study session for lowering γ_t in the SPS and therefore increasing the threshold of the microwave instability in 1998 [4], where the SPS was operated with tunes close to 24. However, big dispersion waves

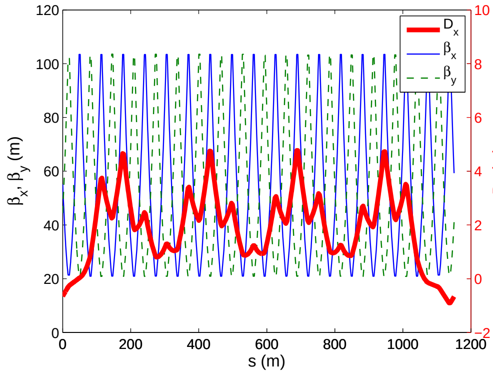

Figure 2: Nominal optics (Q26) of the SPS (1/6 of the circumference). The phase advance per FODO cell is close to $\pi/2$, resulting in a total phase advance of $\mu_x \approx 4 \cdot 2\pi$ per arc and thus 4 big oscillations of the dispersion function.

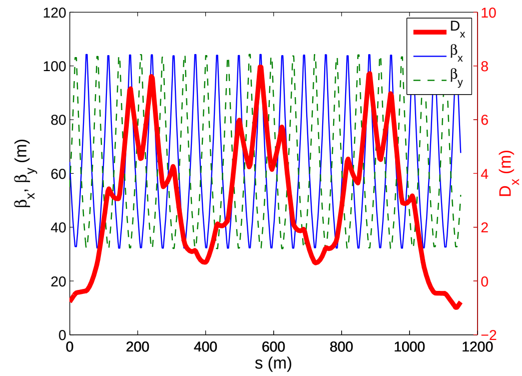

Figure 4: New optics with low γ_t (Q20). The phase advance per cell is reduced to $3/8\pi$ resulting in a phase advance of $3 \cdot 2\pi$ per arc with 3 big dispersion oscillations in the arcs and dispersion suppression in the straight sections.

are excited around the ring and machine operation close to these "resonant" tunes is in general difficult. On the other hand, sufficiently far away from these resonant tunes, γ_t scales indeed linear with Q_x and can thus be lowered by simply reducing the horizontal phase advance around the ring. Significant changes of the horizontal tune may lead however to considerable dispersion in the straight sections, as the missing dipole scheme was optimized for dispersion suppression in the nominal optics. Nevertheless, dispersion can be suppressed in the straight sections by setting the phase advance along the 16 FODO cells per arc close to multiples of 2π (I-transformer). Then, resonant dispersion waves are excited in the arcs, while the missing dipoles at the arc extremities cause only minor residual dispersion in the long straight sections.

One of the possible solutions with resonant arcs and lower γ_t is obtained by reducing the phase advance in each

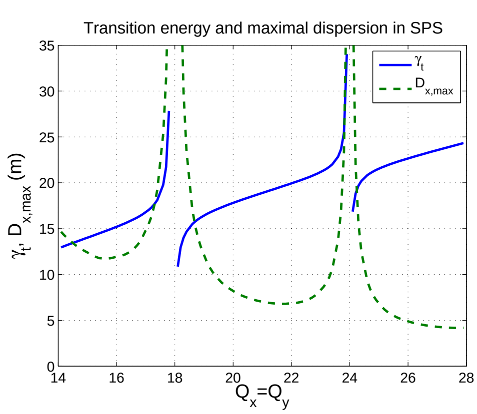

Figure 3: γ_t and maximal dispersion around the ring as function of horizontal tune (Q_y set equal to Q_x). For Q_x close to multiples of the machine super periodicity 6, resonant oscillations of the dispersion function are induced which result in the asymptotic behavior of γ_t.

of the arcs by 2π. In this way, the phase advance per arc is close to $\mu_x, \mu_y \approx 3 \cdot 2\pi$ and the machine tunes are $Q_x, Q_y \approx 20$ ("Q20 optics"). Figure 4 shows the corresponding optics function for one super-period of the SPS. Note that in comparison to the nominal optics ("Q26"), the dispersion function follows 3 instead of 4 big oscillations along the arc with peak values increased from 4.5 m to 8 m. The transition energy is lowered from $\gamma_t = 22.8$ in the nominal optics to $\gamma_t = 18$ (cf. Fig. 3). Therefore, η is increased by a factor 2.85 at injection and 1.6 at extraction energy (cf. Fig. 1). Note that the maximal β-function values are the same in both optics. The fractional tunes have been chosen identical with the nominal optics in order to allow for direct comparison in experimental studies. A summary of the optics parameters is given in Table 1.

Table 1: Optics parameters

SPS optics	**Nominal**	**Low γ_t**
Horizontal tune Q_x	26.13	20.13
Vertical tune Q_y	26.18	20.18
Maximal β-functions β_x, β_y	105 m	105 m
Minimal β-functions β_x, β_y	20 m	30 m
Maximal dispersion D_x	4.5 m	8 m
Transition energy γ_t	22.8	18
Slippage factor η at 26 GeV/c	0.62e-3	1.8e-3
Slippage factor η at 450 GeV/c	1.9e-3	3.1e-3
Phase advance per cell μ_x, μ_y	$4 \cdot 2\pi/16$	$3 \cdot 2\pi/16$

EXPERIMENTAL STUDIES

As no hardware modification is needed for the above described Q20 optics in the SPS, first experimental studies were performed already in 2010. It was soon realized that due to the smaller natural chromaticity and the considerably increased dispersion in the arcs, significantly smaller

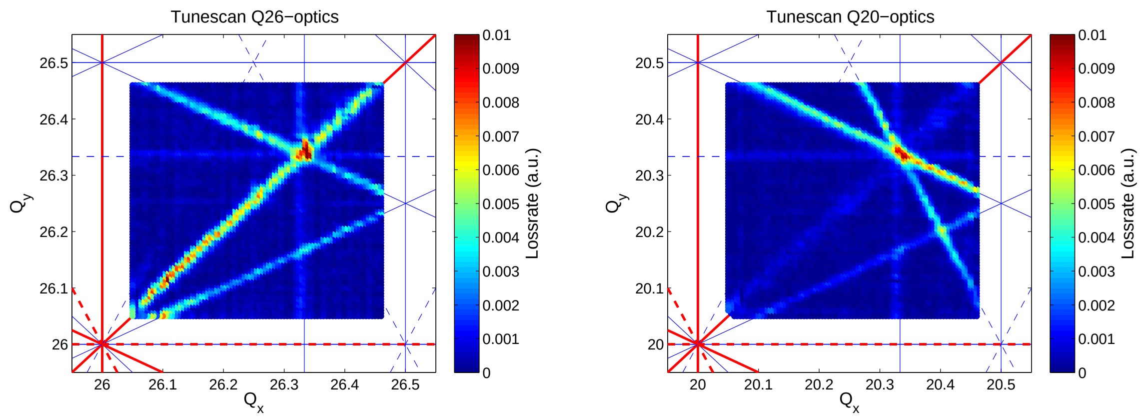

Figure 5: Experimental tune scans in the SPS with the nominal (Q26) optics (left) and the low γ_t (Q20) optics (right). The color-code indicates the loss rate during a dynamic scan of the fractional tunes. The underlying tune diagram shows resonances up to third order, with systematic resonances in red and non-systematic in blue. Solid lines correspond to normal and dashed lines to skew resonances.

sextupole gradients are needed for chromaticity correction. On the other hand, the location of the sextupole magnets in the lattice is optimized for the nominal optics. Tune-scans were performed in both optics in order to compare their resonance behavior. A method originally applied by G. Franchetti [5] and recently revived in space charge studies in the PS was also applied in the SPS: losses are recorded for a single bunch beam of enlarged size during a dynamic sweep of the fractional tunes. The strength of the resonances is then inferred from the slope of the recorded loss function. The resulting resonance diagrams are shown in Fig. 5. Low order resonances can be clearly identified in both optics. A surprisingly strong third order skew resonance is found in the Q20 case. The reason for this is not clear yet. On the other hand, the area close to the present working point ($\nu_x, \nu_y = 0.13, 0.18$) is free of low order resonances in both optics.

The main machine studies with the Q20 optics in 2011 were dedicated to beam stability with high intensity. As reported in [6], clear improvement with respect to longitudinal instabilities with 50 ns beams close to ultimate LHC intensity was demonstrated. Most strikingly, no TMCI was observed up to now in the Q20 optics for single bunches with intensities up to 3.5e11 p/b.

POTENTIAL LIMITATIONS FOR LOWER TRANSITION ENERGY IN THE SPS

In principle, γ_t can be reduced even further (while keeping dispersion in the straight sections low) by adjusting the phase advance in the arcs to $\mu_x, \mu_y \approx 2{\cdot}2\pi$ ($Q_x, Q_y \approx 14$). However, in addition to potential aperture limitations due to increased optical functions, the available RF-voltage could become an important limitation. In particular, the RF-voltage has to be increased according to $V_{RF} \sim \eta$ for keeping the bucket area constant. While this rules out any optics with $\gamma_t \leq 17$ due to the required RF-voltage at injection, it could also prove to become a limitation for the Q20 optics at extraction: already now the maximal available RF-voltage of the SPS 200 MHz cavities is used in the nominal optics at flat top to shorten the bunches for beam transfer to the LHC 400 MHz system. For the same longitudinal emittance, the bunches would therefore be longer in the low γ_t optics. However, controlled longitudinal emittance blow-up is needed in the nominal optics for stabilizing the beam while less emittance blow-up should be necessary in the low γ_t optics. According to theory, the smaller longitudinal emittance required for the same stability in the Q20 optics should then give the same bunch length as the enlarged emittance in the nominal optics [1]. A first indication in this direction was obtained in a direct comparison of the two optics in experiments with the 50 ns LHC beam [6]. The question is then, if beams with this smaller emittance are stable on the flat bottom in LHC itself. These aspects will be addressed in upcoming machine studies: experiments with the 25 ns beam and tests for the injection into LHC are planned for the near future.

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