IMPACT OF LOW TRANSITION ENERGY OPTICS TO THE ELECTRON CLOUD INSTABILITY OF LHC BEAMS IN THE SPS

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Abstract

One of the main limitations for high intensity multi-bunch LHC proton beams in the SPS is imposed by electron cloud instabilities. A new optics of the SPS with lower transition energy was implemented and successfully tested in machine studies. The significant increase of the slippage factor that it provides at injection energy results in the expected increase of the single bunch instability thresholds. In this paper, the impact of this new optics on the electron cloud instability threshold is estimated by using numerical simulations, taking into account the change of the optics functions and the faster synchrotron motion due to the reduced transition energy.

INTRODUCTION

In the presence of many closely spaced proton bunches in the CERN SPS, an electron cloud is formed mainly in the bending magnets through multipacting [1]. This electron cloud build-up is especially critical for LHC-type beams with the nominal 25 ns bunch spacing. The fast instability and transverse emittance blow up caused by the electron cloud is one of the main intensity limitations for LHC-type beams in the SPS [2]. In 2010, a new optics with lower γ_t was proposed [3] for increasing the instability thresholds for transverse mode coupling (TMC) and longitudinal instabilities for future LHC beams with higher intensity. Clear improvement of beam stability due to the significantly increased slippage factor has been demonstrated in recent machine studies [4]. The impact of the new optics on the electron cloud instability (ECI) has not been studied experimentally up to now.

The electron cloud build-up around the ring is not expected to change dramatically with the different optics, as the average beam size is increased by roughly 20% only. This paper will concentrate on the ECI assuming that the electron density in the machine is about the same for the two optics. However, it is not attempted to provide an exact prediction for the instability thresholds in the two optics. It is rather intended to obtain a prediction for the scaling of the ECI threshold between the two cases.

The results presented in the following are obtained with the HEADTAIL [5] tracking code. In the simulation, the electron cloud is represented by a thin slice of macro particles with uniform distribution in the transverse plane. The interaction of the bunch particles with the electron cloud is computed by a Particle-In-Cell (PIC) solver, where bunch slices interact consecutively with the electron cloud. An instability can be triggered, as the motion of subsequent slices is coupled through the distortion of the electron cloud distribution induced by the passing bunch. In order to avoid incoherent emittance growth due to numerical artifacts, the electron cloud is distributed over 192 evenly spaced interaction points. In most of the cases here, it is assumed that the electron cloud is concentrated in the bending magnets. Due to the strong magnetic field, the electrons move freely in the vertical direction but are bound close to the field lines in the horizontal plane. This is modeled by freezing the electron motion in the horizontal plane (strong magnetic field approximation). The electron cloud instability affects then only the vertical plane and can be observed as an exponential growth of the vertical emittance due to the increasing amplitude of the coherent headtail motion.

Table 1: Simulation Parameters

SPS optics	Low γ_t	Nominal
Hor. tune Q_x	20.13	26.13
Vert. tune Q_y	20.18	26.18
$\bar{\beta}_{x,y}$ in LSS	54.6 m	42 m
$\bar{\beta}_x$ in MBB dipoles	45.5 m	34.4 m
$\bar{\beta}_y$ in MBB dipoles	78.4 m	72.3 m
$\bar{D}_x$ in MBB dipoles	3 m	1.8 m
Transition energy, γ_t	18	22.8
Slippage factor η	0.0018	0.00062
Synchrotron tune Q_s	0.017	0.0059
RF-voltage	5.75 MV	2 MV
Chromaticity ξ_x, ξ_y	0	
Norm. emittances $\varepsilon_{x,n}$, $\varepsilon_{y,n}$	2.5 μm	
Bunch length σ_z	0.23 m	
Momentum spread $\delta p/p$ (rms)	0.002	
Relativistic γ (at injection)	27.7	

SCALING OF INSTABILITY THRESHOLD

As the synchrotron motion is significantly faster in the low γ_t optics due the higher slippage factor compared to the nominal SPS optics, it is interesting to study the dependence of the instability threshold on the synchrotron tune Q_s. A series of simulations with varying Q_s was performed using the parameters of the nominal SPS optics at injection as summarized in Table 1. As in the real machine, the RF-voltage has to be increased proportional to the slippage factor η in order to keep the bucket area constant. In this way, the longitudinal bunch parameters like momentum spread and bunch length are independent of synchrotron tune changes. Figure 1 shows the verti-

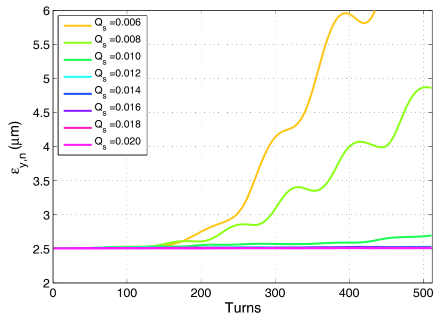

Figure 1: Vertical emittance as function of turns for different synchrotron tunes assuming an electron density of ρ=4.8e11/m^3 and bunch intensity of N_b=1.3e11 p/b.

cal emittance as function of time (turns) for different synchrotron tunes. Note that the instability rise time decreases for higher synchrotron tunes and the bunch becomes stable below a certain threshold.

Existing models [6] for the ECI predict that the threshold electron density ρ_c for the onset of the instability scales linearly with the synchrotron tune Q_s under the assumption that the bunch length is a given parameter. In order to find the instability threshold for a given Q_s, a set of simulations with varying electron cloud density is needed.

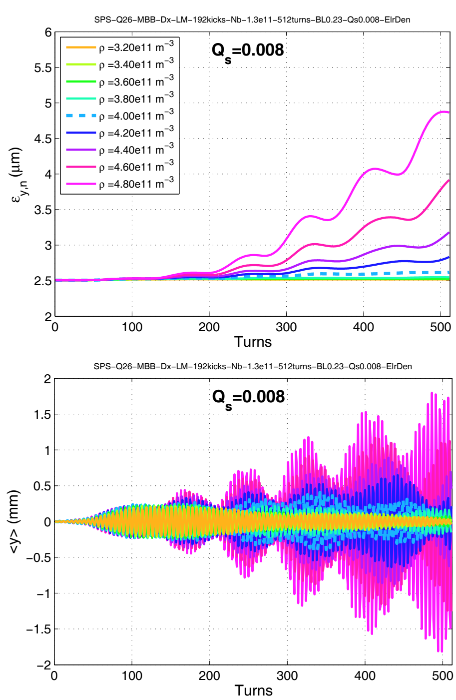

Figure 2: Simulations with N_b=1.3e11 p/b for the nominal optics but with Q_s=0.008. Top: Vertical emittance for different electron cloud densities as indicated by the colorcode. Bottom: Corresponding vertical centroid motion. A dashed line marks the threshold density ρ_c=4e11 p/b.

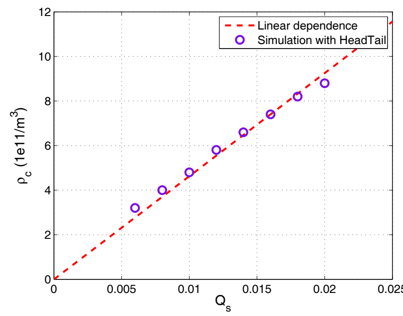

Figure 3: Instability threshold density ρ_c as function of the synchrotron tune for constant bunch parameters. Simulated points are compared with the predicted linear dependence.

Figure 2 shows an example for the same parameters as used in the scan above but fixing the synchrotron tune to $Q_s = 0.008$. Here, the lines correspond to different values of the electron density. Above the threshold density ρ_c (marked by a dashed line), the coherent oscillations start growing exponentially which is observed as coherent emittance growth. In the following, the threshold is defined as the lowest electron cloud density, for which the emittance grows coherently by about 5% within the simulated 512 turns. This kind of simulation is repeated for different synchrotron tunes. The resulting scaling of the threshold electron density is shown in Fig. 3. A linear dependence, in good agreement with the prediction of analytical models, is observed in the simulations.

A similar scan as described above is repeated for varying β-functions. It should be emphasized here, that the machine optics is modelled by HEADTAIL as a uniform focusing channel, i.e. using the smooth approximation. Therefore, only the average β-function is changed in the code which is not reflecting local differences in the beam sizes for different optics. Nevertheless, a rough idea of the impact of different optical functions can be obtained. Fig-

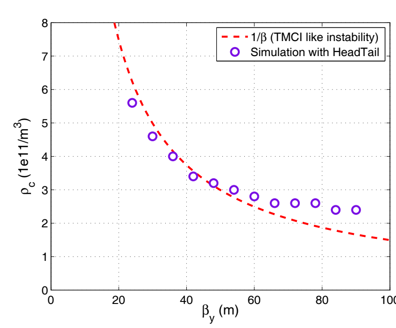

Figure 4: Instability threshold density ρ as function of β_y in the bending magnets. Circles represent the simulated points while the solid line shows a $1/\beta_y$ dependence as obtained in simplified analytical models treating the electron cloud instability as TMCI-like phenomenon.

ure 4 shows the dependence of ρ_c on changes of β_y assuming again that the electron cloud is located in the bending magnets. In the past, the ECI has often been referred to as TMC-like instability and in corresponding analytical models the threshold scales therefore like $1/\beta_y$. However, the situation is more complicated as the electron oscillation frequency ("pinch") is a function of the beam size and thus the wake field represented by the electron cloud depends on the optical functions. Clearly, the simplified models do not incorporate all subtle details of the electron proton interaction causing the ECI, which explains the difference to the scaling observed in the simulation.

IMPACT OF THE NEW SPS OPTICS ON THE INSTABILITY THRESHOLD

The threshold for the electron cloud instability is compared between the nominal SPS optics and the new low γ_t optics using the parameters presented in Table 1. Note that the fractional tunes are exactly the same in both optics, but the integer part is reduced by 6 units in the low γ_t optics. Therefore, the average β-functions in the straight sections as well as in the arcs are increased by up to 30%. Due to the increased dispersion in the bending magnets, the transition energy is reduced from $\gamma_t = 22.8$ to $\gamma_t = 18$ which results in the significantly higher synchrotron tune at injection energy. While high chromaticity in the vertical plane is one

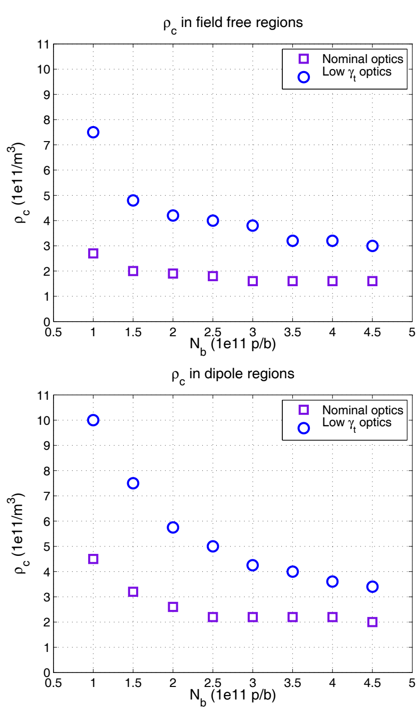

Figure 5: Instability thresholds for various intensities comparing the nominal with the new low γ_t optics of the SPS. Top: Simulation for the field free regions. Bottom: Electron cloud located in the MBB dipoles.

of the measures for mitigating the electron cloud instability, which is routinely applied in the SPS, the simulations are carried out with 0 chromaticity in order to simplify the comparison. Figure 5 shows the obtained thresholds at injection energy as function of the bunch intensity. In the top graph, the electron cloud was assumed to be located in field free regions. There, the threshold is roughly twice higher in the low γ_t optics. The bottom graph shows the simulation results for the electron cloud located in the bending magnets, where the thresholds are on average about 2.3 times higher in the new optics. The difference between the two optics seems more significant at low bunch intensities. Note that in this study, the longitudinal and transverse emittances are assumed to be constant. Further simulations should be performed for higher energy, where the beneficial effect of the lower γ_t is less pronounced. In particular, the ratio of η (and thus of Q_s in the stationary bucket case) rapidly drops from 2.85 at injection to 1.6 at top energy [3]. However, at higher energies the beam could benefit from larger longitudinal emittances, as needed for stabilizing the longitudinal coupled bunch motion. An experimental study is foreseen in one of the next MD sessions.

CONCLUSION AND OUTLOOK

This paper presents a simulation study on the expected threshold for the ECI in the new low γ_t optics in comparison with the nominal SPS optics. From simulations, the threshold electron density is expected to be roughly twice higher for the low γ_t optics at injection energy. Future studies with refined models taking into account the variation of the optical functions around the ring should address not only the instability thresholds but also the incoherent effects due to the interaction of the bunch particles with lattice resonances. Experiments on electron cloud effects in the SPS with the new optics are planned for the near future.

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