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COUPLING AND SPACE CHARGE STUDIES AT THE CERN PSB

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Abstract

In the nominal optics of the CERN PS-Booster (PSB), the fourth order coupling resonance is excited by space charge (Montague resonance [1]) due to the same integer tune values. This resonance can be avoided by changing the tunes to different integers. A new PSB optics is presented and emittance measurements crossing the coupling resonance for the nominal and the new optics are shown.

INTRODUCTION

The PSB is the first ring of the CERN accelerator complex. It operates in a space charge dominated regime due to the demand for high brightness beams in the Large Hadron Collider (LHC) [2]. The space charge force leads to an incoherent tune spread that depends on the energy, the intensity and the transverse and longitudinal parameters of the beam [3]. In the PSB, this tune spread is in the order of $\Delta Q \approx 0.5$ for the LHC operational beams [4]. In the scope of the LHC Injectors Upgrade (LIU) project, the PSB injection energy will increase from 50 MeV to 160 MeV [5]. The new injection energy will allow the acceleration of beams with about twice the brightness while keeping the space charge tune spread at similar values [6].

Space charge can drive systematic resonances of even order [7], at first order approximation, if their harmonic coincides with the machine periodicity, as observed in the CERN Proton Synchrotron [8,9]. The PSB has a periodicity of 16 and operates in the tune regime of both tune integers equal to 4 (Q4Q4 optics). Under these conditions, resonances of 4$^{\text{th}}$ order could be excited. In this paper, analytical studies for those resonances are presented. Moreover, a different working point regime is studied in which the vertical integer tune is equal to 3 (Q4Q3 optics). The response of the operational (Q4Q4) and the new (Q4Q3) optics on the coupling resonance has been studied in the machine for the LIU injection energy and the experimental results are presented.

RESONANCE DRIVING TERMS

The excitation of resonances can be studied using perturbation theory on the non-linear Hamiltonian of the accelerator ring [10]. For the perturbing potential coming from the space charge force of a Gaussian beam [11], the Resonance Driving Terms (RDT) of space charge driven resonances can be analytically evaluated [7, 12]. Figure 1 shows the space charge induced RDT for the 4$^{\text{th}}$ order coupling resonance in the PSB [13]. The optics of the PSB lattice, needed for the evaluation, have been calculated using MAD-X [14]. The Montague resonance, namely $2Q_h - 2Q_v = 0$, is strongly excited in the equal integers tune space (Q4Q4), while it is

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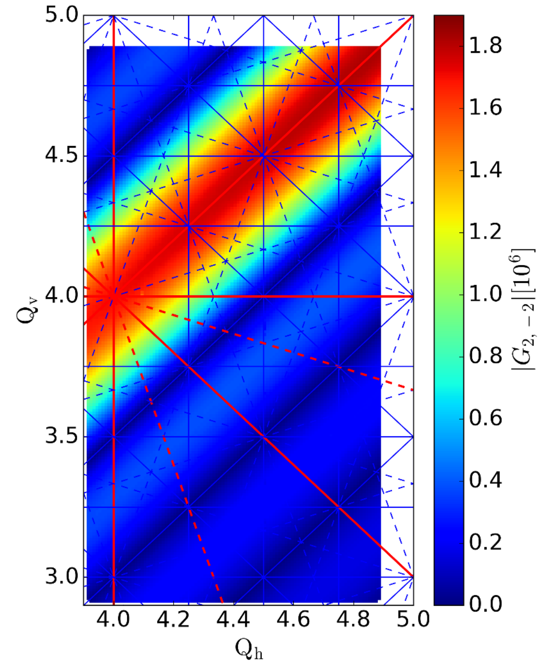

Figure 1: 4$^{\text{th}}$ order RDT coming from the space charge potential of Gaussian distributions for the PSB lattice. The color code corresponds to the amplitude of the respective driving term at each tune.

suppressed in the tune space of uneven integers (Q4Q3) as the corresponding RDT amplitudes are orders of magnitude smaller.

LINEAR COUPLING CORRECTION

In order to study the space charge driven 4$^{\text{th}}$ order coupling resonance excitation, the linear coupling, excited by skew quadrupole components, should be corrected in both optics. Figure 2 shows the RDTs for each available magnet family

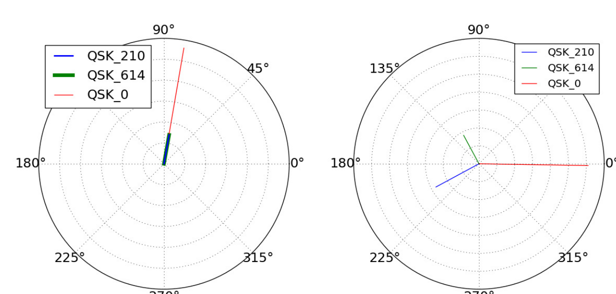

Figure 2: Linear coupling RDTs, phase and amplitude, for the available skew quadrupole magnet families in the PSB, for the Q4Q4 (left) and Q4Q3 (right) optics.

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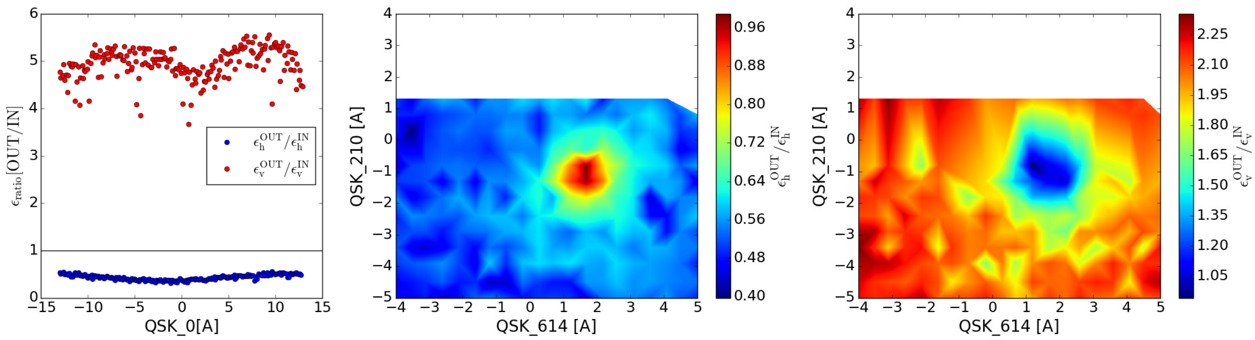

Figure 3: Coupling correction in the PSB. For the Q4Q4 optics (left) the horizontal (blue) and vertical (red) emittance ratios are shown as a function of the powered skew quadrupole current. For the Q4Q3 optics the powered skew quadrupoles current configuration is color coded versus the horizontal (middle) and vertical (right) emittance ratios.

using the optics functions obtained with MAD-X [16] for the two optics. In the Q4Q4 optics, the RDTs of all the available skew quadrupole magnet families are aligned. The chosen family, QSK_0, is most efficient as it generates the biggest amplitude of the driving term (this is a family of 8 magnets, one every other period). In the Q4Q3 optics two groups of magnets forming an orthogonal pair can be identified. This pair, QSK_614 and QSK_210, can form any vector in the RDT space by changing the current configuration.

The closest tune approach is used for empirical correction of the linear coupling by powering the corresponding magnets and testing the effect on the resulting coupling strength. In particular, the horizontal and vertical tunes are crossed and the minimum tune separation directly yields the coupling coefficient. In both optics the tunes are crossed at constant energy, 160 MeV, and are evaluated from the turn by turn data using PyNAFF [17] at the point of the closest approach. In addition, the emittances are measured using beam profiles acquired before and after the crossing. If the coupling is corrected the minimum tune separation should be zero and the emittances unaffected by the crossing.

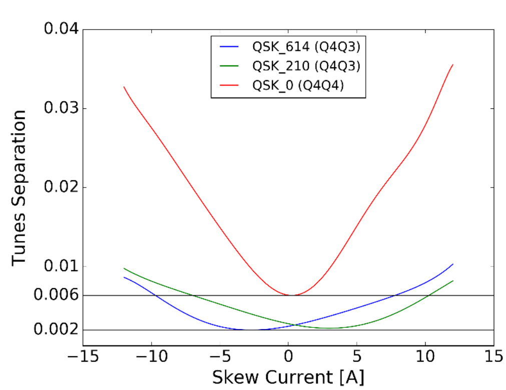

Figure 4: Coupling correction for the Q4Q4 in red and the Q4Q3 optics in blue and green depending on the skew quadrupoles used. The tune separation is plotted versus the skew quadrupole current at the point of the closest approach.

In the Q4Q4 optics, the ratios of the emittances in each transverse plane calculated before and after the crossing are shown in Fig. 3 (left). Both ratios lie far from unity regardless of the skew quadrupoles value, indicating that the emittances in both planes are affected by the crossing of the coupling resonance. Moreover, the natural coupling is quite strong since the minimum separation is in the order of $6 \cdot 10^{-3}$, as shown in Fig. 4. In addition, it cannot be further corrected, since using the skew quadrupoles only enhances the separation, which hints to the Montague resonance as it cannot be compensated with skew quadrupoles [15].

Concerning the Q4Q3 optics, the natural coupling is in the order of $3 \cdot 10^{-3}$ which is almost a factor 2 smaller compared to the Q4Q4 optics, as shown in Fig. 4. The tune separation can be further reduced using either one of QSK_210 or QSK_614 to $2 \cdot 10^{-3}$. Figure 3 (middle & right) shows the horizontal and vertical emittance ratios in the regime of minimum separation as a function of the current configuration. The coupling is fully corrected when both emittance ratios approach unity.

EMITTANCE EVOLUTION

The emittance evolution along the 160 MeV plateau has been studied while crossing the coupling resonance. The

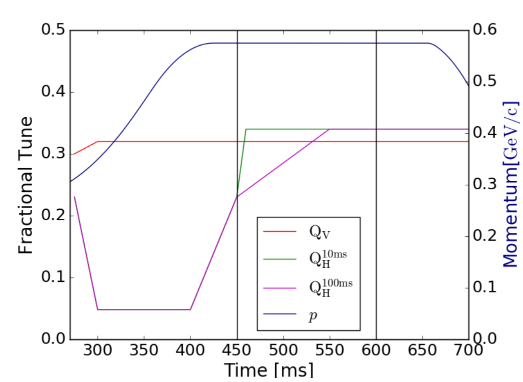

Figure 5: Fractional tunes and momentum along the cycle. The plateau of the momentum corresponds to 160 MeV.

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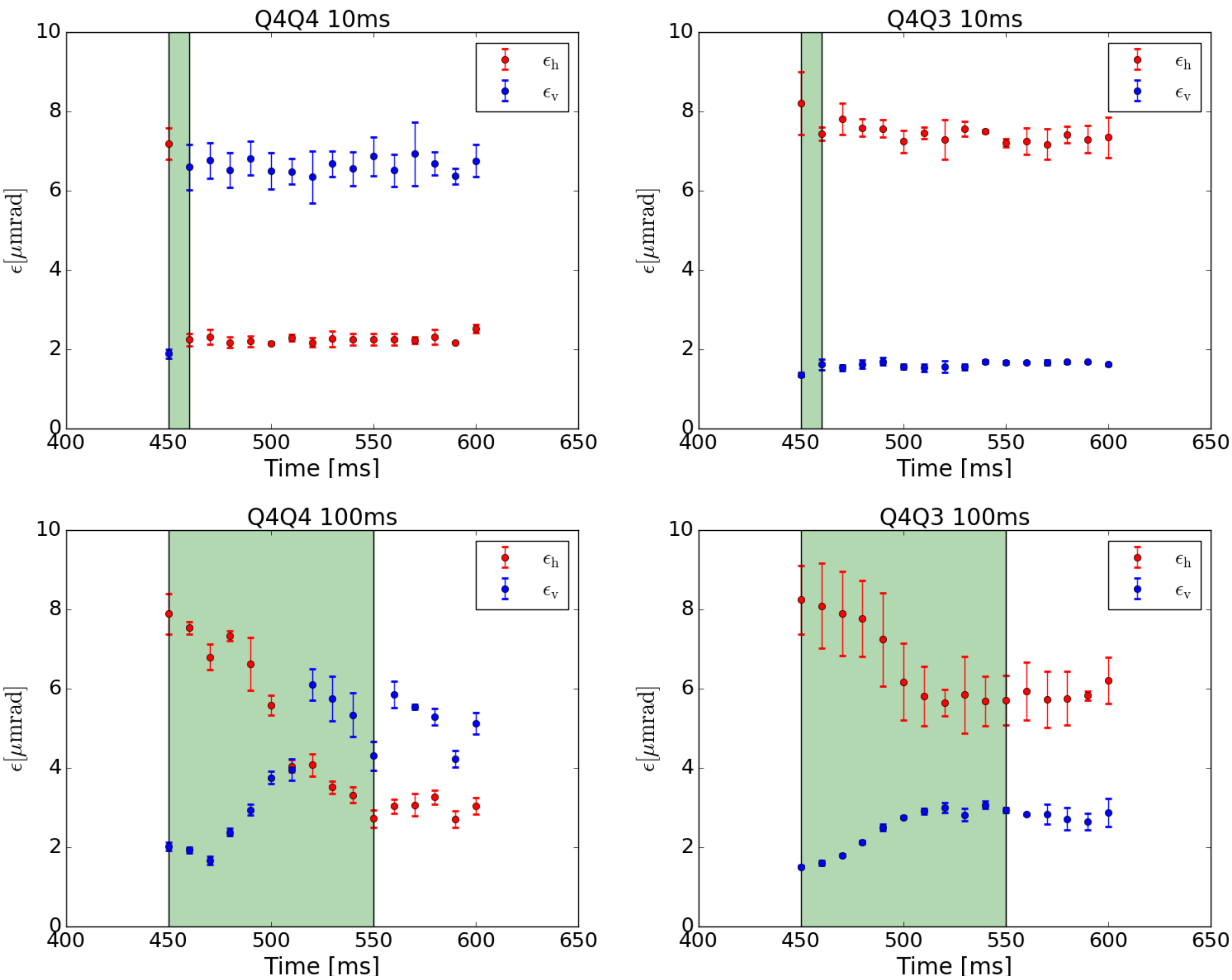

Figure 6: Horizontal (red) and vertical (blue) emittances along the 160 MeV plateau for the Q4Q4 (left) and Q4Q3 (right) optics. The green shaded areas correspond to the time of the tune variation for the resonance crossing, 10 ms (top) and 100 ms (bottom).

experimental configuration is illustrated in Figure 5. The beam is injected on a working point optimized for transmission and then accelerated up to 160 MeV. During the acceleration, a blow-up of the horizontal emittance is provoked by approaching the horizontal integer resonance. This is done in all cases in order to achieve a ratio of $\epsilon_h/\epsilon_v \geq 4$ at the beginning of the flat top, at 450 ms, and a space charge tune spread in the order of $\Delta Q \approx 0.1$ in both planes. The coupling resonance is crossed either in 10 ms or 100 ms to study the effect of the crossing speed on the emittances [18]. The transverse emittances are calculated from beam profiles acquired every 10 ms along the flat top, from 450 ms to 600 ms. The results for both optics are presented in Fig. 6.

The fast crossing of the resonance in 10 ms has a strong effect in the Q4Q4 optics and the emittances exchange completely. On the other hand, in the Q4Q3 optics the fast crossing is almost transparent, as no significant emittance variation is observed in either plane. When the crossing speed is reduced to a tune variation within 100 ms, the coupling resonance is overlapped by the tune spread for a longer time. As a result, the emittances approach each other gradually in both optics. However, in the Q4Q3 optics the emittance exchange is relatively mild while in the Q4Q4 optics a complete exchange is observed.

CONCLUSION

In the PSB the 4$^{\text{th}}$ order coupling space charge driven resonances have been studied analytically. Experimental studies confirm that the proposed Q4Q3 optics with unequal integer tunes is much less affected by coupling, as the Montague resonance is not excited and the linear coupling can be compensated to a large extend. Nevertheless, if the beam interacts with the resonance for an extended period of time, some emittance exchange is observed but much less pronounced compared to the Q4Q4 optics.

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