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STUDIES OF A NEW OPTICS WITH INTERMEDIATE TRANSITION ENERGY AS ALTERNATIVE FOR HIGH INTENSITY LHC BEAMS IN THE CERN SPS

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Abstract

The LHC injector upgrade project (LIU) [1] calls for a twofold increase in intensity of the SPS proton beam. In this paper, we present studies with a new SPS optics called Q22, which has a transition energy in between the one of the operationally used Q20 and Q26 optics. This new optics provides a compromise between the stability of Q20, due to the low transition energy, and the reduced requirements in terms of RF voltage and power in Q26. A non-linear effective model of Q22 has been extrapolated from beam based measurements and used to complement the SPS non-linear optics model. Furthermore the studies of the TMCI threshold performed so far are discussed.

INTRODUCTION

The CERN Super Proton Synchrotron (SPS) is the last machine of the Large Hadron Collider (LHC) injector chain at CERN. In preparation of the High-Luminosity era of the LHC, the LHC injector upgrade (LIU) project aims at doubling the proton beam intensity at SPS extraction compared to present operation.

The transverse mode coupling instability (TMCI) at injection represents one of the most important intensity limitations on the maximum intensity delivered by the SPS. To overcome this performance limitation, the optics of the SPS had been changed from the so-called Q26 optics integer tunes of 26 to the Q20 low gamma transition optics with integer tunes of 20 [2]. This allowed for an almost 3-fold increase of the TMCI threshold [3] and provided thus enough margin for the future intensity goals. However, due to the lower transition energy the required RF power for beam loading compensation during the ramp could become a limitation in the Q20 optics even after the foreseen RF upgrade. Therefore the Q22 optics [4] with integer tunes of 22 and intermediate transition energy was tested with the aim of finding a good compromise between TMCI threshold and RF power requirements during the ramp.

The unprecedented beam intensity to be delivered by the injector requires a full non-linear optics model for the SPS in order to understand coherent and incoherent effects and for optimizing transmission. In fact, because the increased intensity will result in a larger space charge induced tune spread, non-linear magnetic multipoles become an essential ingredient to describe correctly the beam dynamics.

In this work a detailed non-linear magnetic model of the SPS has been developed using beam measurements of the non-linear chromaticity. Two sources of non-linearities have been identified as main contributors: a) Odd multipoles produced by the error harmonics of the main dipole magnets. b) Residual fields in sextupole and octupole corrector magnets. Residual fields have a significant contribution to the chromatic detuning at the SPS flat bottom. In a previous work [5, 6] the dependency of sextupoles magnetic field on the cycle composition and therefore on the magnetic history of the optics was already observed. A mitigation strategy, that consists in pulsing the chromatic sextupoles to their maximum current at the end of each cycle, is already in place and applied during normal operations.

On the other hand, there is so far no measure in place to ensure reproducible residual fields in the Landau octupoles as well as the individual sextupole and octupole corrector magnets of the SPS. A short magnetization-demagentization cycle in the beam-out segment of all SPS magnetic cycles will be implemented for all non-linear magnets during the 2018 run.

NON-LINEAR OPTICS FROM CHROMATICITY MEASUREMENTS

A measurement of the chromatic detuning, extended over a wide range of momentum deviation (dp/p) was set up. In order to disentangle the contribution of different sources of multipolar fields, the same measurement was repeated on 3 different optics (Q20, Q22, Q26). Since each optics has different dispersion (Fig. 1) and betatron functions, each configuration adds up the contributions of the multipole error with different weights. An effective model has been built by fitting the strength of the multipolar error sources in order to reproduce the experimental observations. The fit is performed by calculating a chromaticity response matrix with MAD-X [7], containing the change in chromaticity due to each multipolar error source in the optics as described in [8]. A singular value decomposition is used to invert the response matrix and finally obtain the multipoles strength from a set of chromaticity measurements for Q20, Q22 and Q26 optics. In order to observe the dependency of the multipoles errors in the dipoles on their magnetic history, the chromaticity measurement has been repeated in different machine configuration. For this purpose various ion cycles providing Xe ions for fixed target experiments in the CERN north area were exploited. In fact since these experiments

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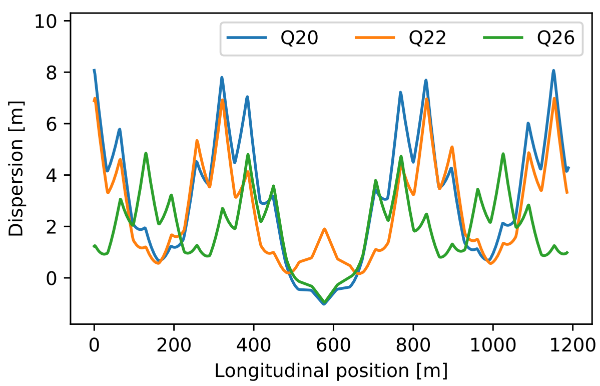

Figure 1: Horizontal dispersion for Q20, Q22 and Q26 in one sextant of the SPS. The very different dispersive pattern of each optics allows to sample the non-linear multipoles in a different way.

require ions with several different energies it was possible to study the effects induced by magnetic hysteresis by placing the test cycles, used to measure chromaticity in the different optics, after the ion cycles as shown in Fig. 2.

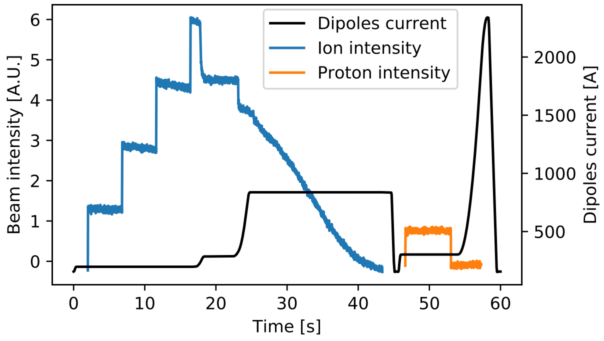

Figure 2: Plot of the beam intensity and dipoles current showing the typical cycle configuration used to carry out measurements, with the proton cycle (orange) used for the chromaticity measurement after the ion cycle (blue).

NON-LINEAR CHROMATICITY MEASUREMENTS OPTIMIZATION

Obtaining non-linear information from a chromaticity measurement requires to sample the far dp/p extremes where the chromaticity departs from the linear behavior. Therefore some effort has been devoted to the optimization of the tune measurement, allowing to widen the achievable dp/p span. A good tune measurement can be achieved only as long as the bunch moves like a single particle, therefore a small decoherence is mandatory. Such a condition is obtained by minimizing the momentum spread of the beam. A very low RF voltage allows to keep the momentum spread to a minimum value. Therefore a total voltage of 300 kV was used, a value which is one order of magnitude smaller than the nominal SPS working condition. In order to avoid beam instabilities due to low chromaticity, a low bunch intensity of $\simeq 2 \cdot 10^{10}$ protons has been used. This intensity is sufficient to provide an acceptable tune measurement by means of the Base-Band Tune Meter (BBQ [9]), a wide dynamic range beam position monitoring system developed specifically for tune measurements. Figure 3 shows the results of a typical chromaticity measurement for the different optics, along with the result of the combined fit.

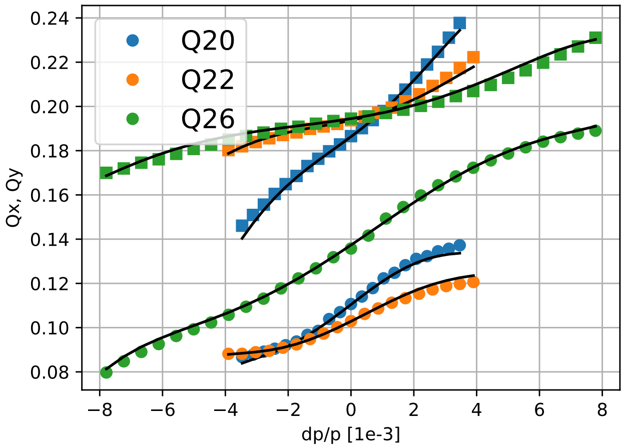

Figure 3: Horizontal (dots) and vertical (square) fractional tune measured during a typical momentum scan for Q20, Q22 and Q26 for an ion top momentum of 71.7 GeV proton equivalent. Because of the different dispersion in the 3 optics, the dp/p range has been adjusted in order to cover the same radial excursion. The chromaticity computed from the effective model obtained from the fit of the 3 measurements is also shown (black curves).

MULTIPOLAR MAGNETIC ERRORS FIT AND RESULTS

The multipolar optics model is obtained by fitting individual sources of error in order to reproduce the chromaticity measurements. For this purpose, a MAD-X model of the SPS containing all the known sources of error has been prepared. The model includes 4 parameters that take into account remanent fields in focusing and defocusing chromatic sextupoles (*ksremf* and *ksremd*) and octupoles (*koremf* and *koremd*). SPS dipoles are known to be a source of higher order multipoles, but because of the symmetry of the poles arrangement, only odd multipoles are allowed in a dipole. The SPS includes two different kinds of dipoles (MBA and MBB). To account for multipoles up to the seventh order 6 parameters have been introduced in the model to represent sextupolar (b_{3a}, b_{3b}), decapolar (b_{5a}, b_{5b}) and decatetrapolar (b_{7a}, b_{7b}) multipoles. Figure 4 shows the result for every parameter, for each different ion cycle top energy, obtained with a combined fit of the measurements in Q20, Q22 and Q26 optics, obtained at the SPS flat bottom (26 GeV proton momentum). As expected the remanent fields in the octupole and chromatic sextupole magnets are almost independent on the ion cycle energy, on the other hand some energy depen-

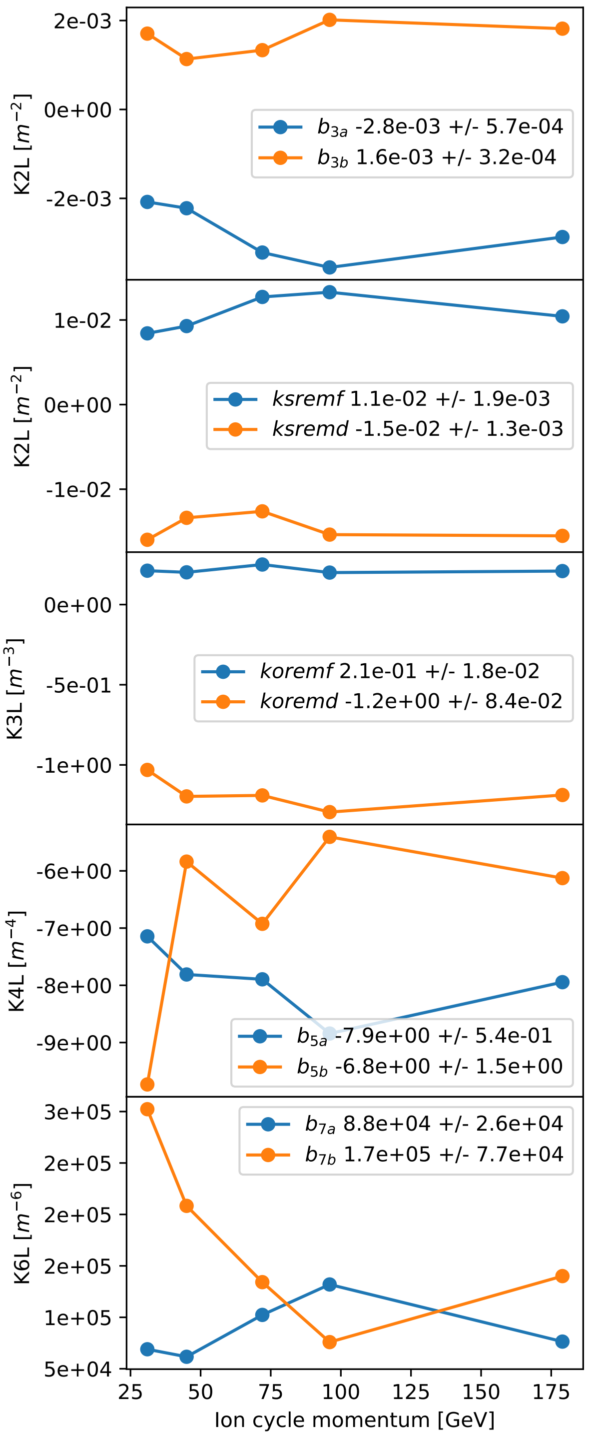

Figure 4: Fit of the multipolar magnetic errors, for 5 different energies of the ion cycle. Each point is obtained from a combined fit for the 3 optics (Q20, Q22, Q26). The values in the legend are obtained from the average over the different ion cycle energies and their standard deviation.

dency is observed for the error multipoles in the dipoles, in particular for the higher order ones, however the uncertainty level of the fit makes it difficult to draw a conclusion.

TMCI THRESHOLD

The TMCI threshold has been characterized for the Q22 optics by injecting single bunches into the SPS. The bunches had a longitudinal emittance of around 0.32 eVs and the optics was set up with a slightly positive chromaticity to ensure the suppression of the mode zero head-tail instability excited at negative chromaticity. The total intensity 200 ms after the injection into the SPS is measured with a beam current transformer and compared to the intensity extracted from the injector, the Proton Synchrotron (PS). The measurement was repeated while ramping up the bunch intensity, obtaining a picture in terms of stability range. Figure 5 shows that the single bunch intensity in the SPS is limited to $2.5 \cdot 10^{11}$. The intensity is lost due to the very fast TMCI before the bunch intensity measurement happens in the SPS. Thus, the TMCI threshold for the Q22 optics has been estimated at $2.5 \cdot 10^{11}$ protons per bunch for a longitudinal emittance of 0.32 eVs, consistent with predictions from previous studies [4].

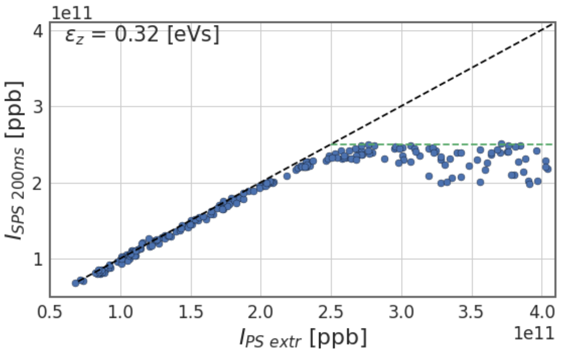

Figure 5: TMCI measurement in the SPS. The plot shows the bunch intensity measured after 200 ms as a function of the injected intensity. The green dashed line represents the TMCI threshold determined from the measured data.

CONCLUSION

Low intensity bunches allowed to operate the SPS with very close to zero chromaticity and low total RF voltage, making it possible to acquire a wide dp/p range chromatic detuning scan. Combining together measurements acquired with 3 optics with different dispersion and betatron functions, it was possible to obtain a detailed picture of the non-linear chromaticity and therefore reconstruct an effective non-linear optics error model, that includes multipoles up to the seventh order. Measurements have been repeated in different cycle configurations in order to investigate the dependency of the multipole errors in the main magnets on their magnetic history, further studies will be needed in order to draw a final conclusion on this subject. Furthermore, the TMCI threshold was characterized in the Q22 optics for the first time and a threshold of $2.5 \cdot 10^{11}$ protons per bunch was observed for a longitudinal emittance of 0.32 eVs. This instability threshold is compatible with the LIU target intensity of $2.7 \cdot 10^{11}$ protons per bunch, considering that the nominal longitudinal emittance is 0.35 eVs.

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