IMPROVED METHODS FOR THE MEASUREMENT AND SIMULATION OF THE CERN SPS NON-LINEAR OPTICS

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Abstract

Good knowledge of the non-linear properties of the SPS lattice is crucial for modeling and optimizing the machine performance in the presence of collective effects leading to incoherent tune spreads such as space charge, e-cloud and beam coupling impedance. In view of the LHC injectors upgrade (LIU) project and the future SPS operation in a regime dominated by such collective effects, detailed measurements of the SPS non-linear chromaticity and detuning with amplitude have been performed for the two optics configurations presently available for LHC type beams. The measurement results are used to fit systematic multipole components to the main magnets of the SPS MADX model as a basis for the non-linear machine model that can be used for beam dynamics simulations. The implications for the operation of the SPS with the LIU beam parameters are discussed.

INTRODUCTION

The LHC injectors upgrade project (LIU) aims at consolidating and upgrading the existing accelerator chain at CERN in view of the significant increase in beam intensity and beam brightness required for the High Luminosity LHC (HL-LHC) project. The interest in studying the non-linear optics of the SPS lattice is two-fold. First, a good knowledge of the non-linear properties is crucial for modeling and optimizing the machine performance in the presence of collective effects leading to large incoherent tune spreads, e.g. space charge, e-cloud and beam coupling impedance. Second, the future high beam intensity might require using the Landau octupoles for suppressing coherent beam instabilities [1] and the impact on incoherent effects needs to be understood.

The non-linear chromaticity of the SPS in the nominal optics configuration at the 26 GeV/c injection plateau was studied in a series of measurements between 2000 and 2006 [2, 3]. The aim of these measurements was to establish a non-linear optics model by assigning systematic multipole components to the main lattice magnets in order to reproduce the chromatic properties of the SPS.

In 2012 a new optics with lower transition energy has become operational for LHC beams in order to overcome coherent instabilities for the beam intensity required in the future [5–7]. This optics has integer tunes of 20 in both planes and is therefore called Q20 optics, while the nominal optics with integer tunes of 26 is called Q26. As described below, a series of detailed measurements of the non-linear lattice properties was performed in 2015 directly comparing the two optics at the 26 GeV/c injection plateau.

NON-LINEAR CHROMATICITY

The chromatic properties of the SPS at the 26 GeV injection plateau are dominated by remanent fields and therefore depend on the magnetic history of the machine. All measurements described here were thus performed in the same super-cycle composition (SFTPRO cycle for fixed target physics and flat bottom measurement cycle).

Figure 1 (left) shows the non-linear chromaticity for the Q20 optics measured with a low intensity single bunch beam ($2 - 4 \times 10^{10}$ p/b). Each data point was obtained by averaging multiple tune acquisitions with the SPS BBQ system [8] along the injection plateau. Five measurements like this were recorded for each momentum setting. While for a given momentum offset the horizontal tune is well reproducible, a relatively large spread is observed in the vertical plane (blue dots). This spread comes mainly from the beam coupling impedance, which in the case of the SPS induces a negative tune shift with intensity in the vertical plane but practically no coherent detuning in the horizontal plane [9, 10]. This systematic effect was taken into account in the analysis by normalizing the vertical tunes to an intensity of 4×10^{10} p/b (red dots) as shown in Figure 1 (right) for the data points recorded with $dp/p = 0.0029$. With this correction the measured chromatic detuning in the vertical plane shows a spread as small as in the horizontal plane.

Figure 2 shows the measurement results of the non-linear chromaticity for the two SPS optics configurations. The accessible range of dp/p without particle loss at aperture limitations is much smaller in the Q20 optics due to the

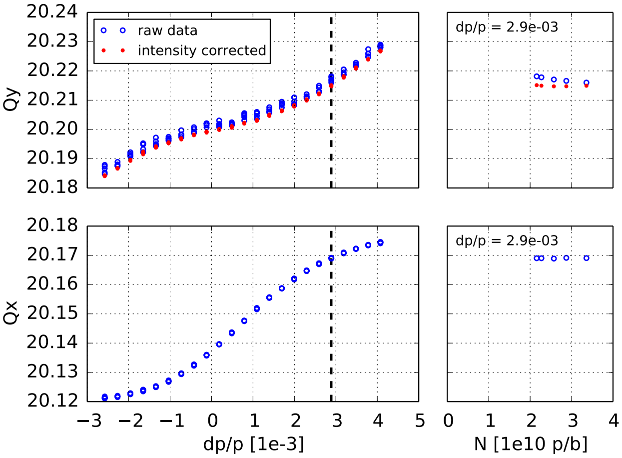

Figure 1: Measured chromatic detuning in the Q20 optics with raw and intensity corrected data (left) and illustration of the correction procedure for a selected momentum setting (right) for vertical (top) and horizontal (bottom).

Table 1: Distribution of Multipolar Errors in the SPS

error order	6-pole		10-pole		14-pole		12-pole		6-pole		8-pole	
chromaticity order	$Q'_{x,y}$		$Q'''_{x,y}$		$Q'''''_{x,y}$		$Q''''_{x,y}$		$Q'_{x,y}$		$Q''_{x,y}$	
variable name	b3a	b3b	b5a	b5b	b7a	b7b	b6f	b6d	b3f	b3d	b4f	b4d
element	MBA	MBB	MBA	MBB	MBA	MBB	QF	QD	LSF	LSD	LOF	LOD
magnet type	dipoles						quadrupoles		sextupoles		octupoles	

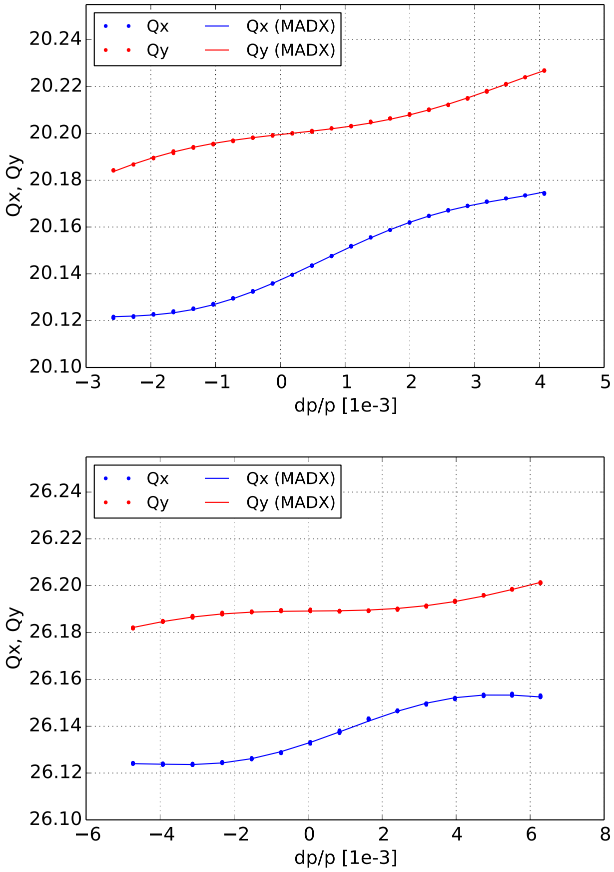

Figure 2: Measured tunes versus relative momentum deviation for the Q20 (top) and the Q26 (bottom) optics at 26 GeV/c together with the combined MADX model obtained by a SVD analysis applied to both measurements at the same time (blue and red lines).

larger dispersion in the arcs. Table 1 describes the distribution of systematic multipolar errors due to remanent fields in the SPS that are chosen in order to reproduce the observed non-linear chromaticities. In contrast to previous studies [3], the octupole errors are assumed here to arise from remanent fields in the Landau octupoles themselves instead of the main quadrupoles (for which an octupole component is not an allowed error multipole due to symmetry). Fringe fields are included in the MADX-PTC model.

Table 2: Multipolar Components Obtained From Matching. Values correspond to integrated strengths in MADX units.

	Q20	Q26	Q20	Q26
	(individual fits)		(combined fit)	
b3a	+0.00195	+0.00120	-0.00392	
b3b	-0.00315	-0.00171	+0.00376	
b3f	-	-	+0.0159	
b3d	-	-	-0.0203	
b4f	+0.803	+1.060	+0.818	+0.878
b4d	-0.530	-0.309	-0.766	-0.225
b5a	-13.3	-15.4	-14.0	
b5b	-4.47	-10.4	-6.34	
b6f	-2100	-1880	-1810	
b6d	+4010	+4000	+5160	
b7a	+301000	+340000	+302000	
b7b	-154000	+220000	-110000	

Similar to the method described in [3], a response matrix of the non-linear chromaticity as a function of the individual multipole components was generated using the SPS model in MADX-PTC [4]. A least squares minimization based on the Singular Value Decomposition (SVD) algorithm is used for fitting the multipole components of the model to reproduce the measurements. First, the two data sets were treated individually. The resulting multipole errors found by this approach are summarized in Table 2. The sextupolar errors were attributed only to remanent fields in the SPS dipole magnets. They should be the same in the two optics as the dipoles have the same magnetic cycle in both cases. However, it appears that larger values for b3a and b3b are needed to reproduce the linear chromaticity in the Q20 optics despite its larger dispersion function. The fitted sextupole components create a relatively large linear chromaticity of about 4 (2.9) in horizontal and 12 (3.8) in vertical for the Q20 (Q26) optics. In order to explain the difference between the two optics, there have to be additional sextupole components in the machine not yet taken into account. A good candidate are residual fields in the chromaticity sextupoles themselves.

In a second step an attempt was made to establish a set of multipole components that can describe the measured non-linear chromaticities in the two optics consistently by applying a combined SVD. This allows to impose additional constraints on the fit parameters and thus to determine the higher order multipole components more accurately. The result is shown in Fig. 2 (red and blue lines) and the corresponding multipole components in Table 2. In addition to the remanent field in the chromaticity sextupoles, it was necessary to introduce independent remanent fields in the Landau octupoles. This might be due to the fact that their settings in the SFTPRO cycle had changed in between the two measurements and these octupoles are presently not demagnetized and not even ramped to a defined current at the end of an SPS magnetic cycle. Note that the fitted remanent fields in the sextupole and octupole magnets are of the order of 1% of their maximum field strength. For comparison, a remanent field of around 3‰ was measured for the old SPS chromaticity sextupoles when ramping them to their maximum current and back to zero [11] (they were about 10 times weaker compared to the present SPS sextupoles).

Apart from sextupole and octupole errors, all higher order multipole components considered here can be adjusted such that the chromatic properties of the SPS can be reproduced for both optics consistently.

AMPLITUDE DETUNING

The detuning with amplitude was measured for both optics and in both planes for different settings of the Landau octupole knobs as shown in Fig. 3 (the knob values correspond to the strength in MADX units). Due to the flat SPS vacuum chambers, relatively large amplitudes (i.e. actions $2J$) could be reached in the horizontal plane while in the vertical plane, larger octupole strengths had to be used due to the limited range of achievable amplitudes. There is an offset between the detuning predicted by the non-linear optics model of the SPS developed above (combined SVD) and the measured detuning (except for vertical detuning in Q26). This discrepancy might be due to octupole errors not yet taken into account, or the dependence on the magnetic history due to the change of settings for the measurements.

In both optics, the measured difference of the vertical detuning for two settings of the LOD octupoles is about 15% smaller compared to the MADX single particle prediction. According to analytical calculations [12, 13], a reduced detuning in the measurement is expected due to the relatively small kick amplitude compared to the normalized emittance (between 1 and 2 μm) and the large anharmonicity a_{yy} induced by the LODs used in the experiment (5000 1/m – 8000 1/m). This effect was studied in macro particle simulations using PyHEADTAIL [14], where the experimental scenario of the measurement was reproduced. Preliminary results show however that the expected reduction of the measured detuning is much smaller than 15%. Further studies in this direction will be performed. Another possible explanation could be beta-beating at the location of the octupoles. On the other hand, investigations are also needed in order to exclude missing strength or wrong calibration of the LODs, or wrong BPM calibration (which were used to determine the actions).

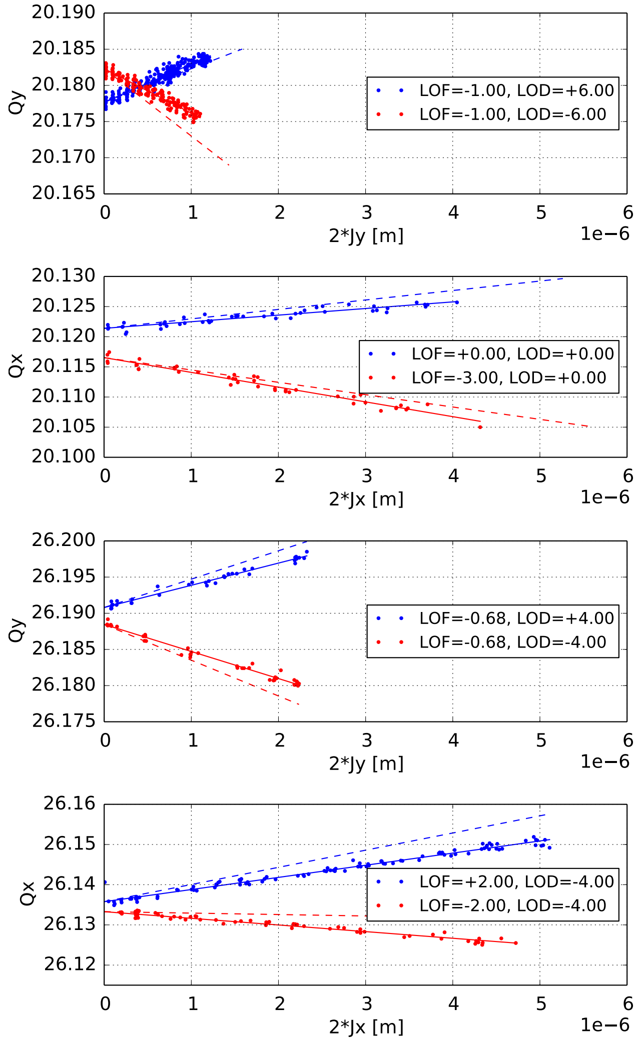

Figure 3: Measurements of amplitude detuning for different octupole settings as indicated in the labels (in MADX units) for both planes in the Q20 optics (top plots) and in the Q26 optics (bottom plots). Solid lines indicate a linear fit to the measurement, dashed lines the single particle prediction from the combined MADX model described above.

CONCLUSIONS AND OUTLOOK

Averaging the tune measurement on the injection plateau and correcting for the detuning due to the beam coupling impedance allows for a precise measurement of the nonlinear chromaticity of the SPS. Performing a combined SVD analysis on the measurements with two different optics yields consistent high order multipole components, but it appears as if there are important contributions to the chromatic detuning coming from remanent fields in sextupoles and octupoles. Future studies will be performed deploying a de-magnetization of these magnets with the hope to improve the agreement of the model with the measured amplitude detuning.

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