IMPROVED ALGORITHMS TO DETERMINE THE NON-LINEAR OPTICS MODEL OF THE SPS FROM NON-LINEAR CHROMATICITY

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Abstract

In recent years several measurements of the SPS non-linear chromaticity have been performed in order to determine the non-linear optics model of the SPS machine at injection energy for different cycles. In 2006 additional measurements have been performed at injection and during the ramp for the cycle used to accelerate the LHC beam. New and more robust matching algorithms have been developed in 2006 to fit the model to the measurements up to arbitrary chromatic order. In this paper we describe the algorithms used in the analysis of the data and we summarize and compare the results from all experiments.

MEASUREMENTS AT 26 GEV

A total of 3 measurements of the SPS non-linear chromaticity have been done at 26 GeV. The 2002 and 2004 experiments have been already described in [1, 2, 3]. The third was performed in 2006. A new SPS model that includes multipolar errors with up to 14 poles together with a more robust matching algorithm allow now a consistent analysis of all the existing data. Table 1 describes the distribution of multipolar errors in the SPS that we have chosen in order to reproduce the observed non-linear chromaticities. Note that octupolar errors are not natural multipoles of quadrupoles. However, we have assumed that these multipoles may arise in quadrupoles due to the radiation damage or assembly tolerances. The multipolar components shown in the table are fitted to reproduce the measured tunes versus relative momentum deviation.

Two fitting algorithms were developed and tested. The first method was based on the computation of a response matrix of non-linear chromaticity terms versus multipole strength. The chromatic terms are computed with the PTC module of MADX [4] and the iterations and the response matrix inversion are carried out with a Python code. The second method is entirely based in MADX, simply computing the tunes at different energy offsets and inferring the chromatic terms from a polynomial fit. Both methods gave same results being the second slightly faster.

The experimental measurements together with the matched model fit are shown in Figs. 1, 2 and 3, corresponding to the years 2002, 2004 and 2006 respectively. The existence of high order multipoles in the new model allows a better matching than in previous analyses [2, 3]. In 2002 and 2004 the same intensity of 4×10^{10} protons per bunch was used. The 2006 experiment had the nominal LHC beam intensity of 1.1×10^{11} ppb. Experiments of 2004 and 2006 were done using the LHC machine cycle while the 2002 cycle was different. Note that the measurement in 2006 has a different momentum range due to a an instability at negative chromaticity arising at $dp/p = -1 \times 10^{-3}$. Indeed an extrapolation of the horizontal tune in Fig. 3 towards lower dp/p would yield a larger tune, hence the negative chromaticity at this point. Previous years did not suffer from the negative chromaticity instability because the intensity was lower.

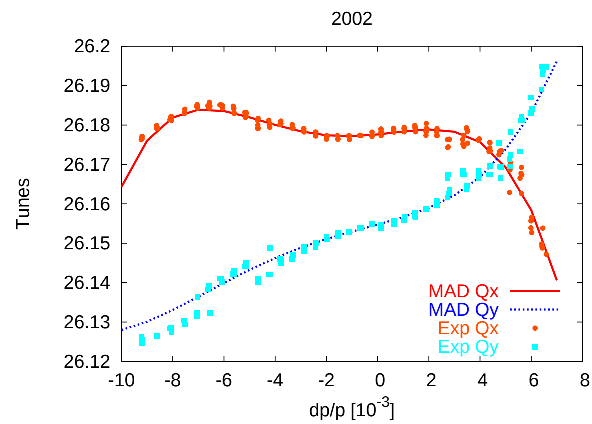

Figure 1: Tunes versus relative momentum deviation from the 2002 experiment at 26 GeV and 4×10^{10}ppb together with the matched model.

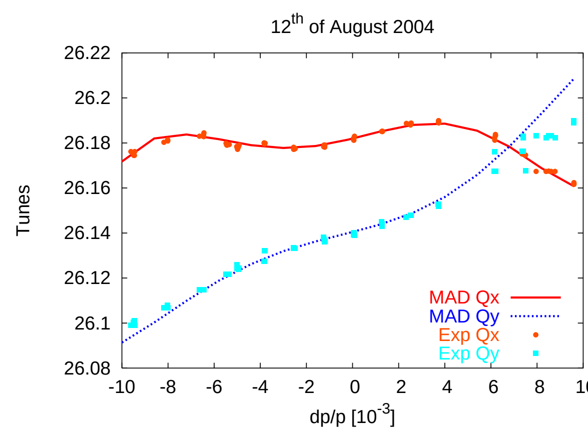

Figure 2: Tunes versus relative momentum deviation from the 2004 experiment at 26 GeV and 4×10^{10}ppb together with the matched model.

The matched multipolar components are shown in Table 2. A poor agreement is found between the three different cases. The reasons for this discrepancy could be the differences in: the machine cycles, the beam intensities and the relative momentum ranges. The bottom of the table also shows the strength of the SPS octupoles as they were set during the measurements.

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Table 1: Description of the distribution of the multipolar errors in the SPS

error order	sextupole		decapole		14-pole		octupole		12-pole	
chromaticity order	$Q'_{x,y}$		$Q'''_{x,y}$		$Q'''''_{x,y}$		$Q''_{x,y}$		$Q''''_{x,y}$	
variable name	b3a	b3b	b5a	b5b	b7a	b7b	b4f	b4d	b6f	b6d
element	mba	mbb	mba	mbb	mba	mbb	qf	qd	qf	qd
magnet type	Main Dipoles						Main Quads			

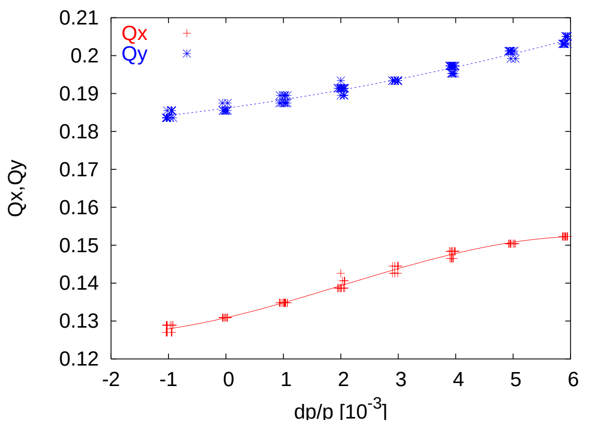

Figure 3: Tunes versus relative momentum deviation from the 2006 experiment at 26 GeV and 1.1×10^{10}ppb together with a fit.

Table 2: Multipolar components as obtained from matching for the different experiments. These values correspond to integrated strengths in MAD units

	2002	2004	2006
b3a	0.00073	-0.00038	-0.00058
b3b	-0.00262	-0.00103	-0.00128
b4f	0.0915	-0.0054	0.0612
b4d	0.0115	-0.2260	-0.2730
b5a	-7.5	6.9	9.2
b5b	-7.2	5.6	-11.8
b6f	-1548	-243	0
b6d	-5571	1728	0
b7a	0.0	-69138	0
b7b	0.0	5992	0
LOFK3	(-0.875)	(0.0066)	(0.0)
LODK3	(0.0)	(-0.967)	(0.0)

SYSTEMATIC ERROR ANALYSIS

Two potential sources of systematic errors have been identified:

- Optical errors in the machine cause the multipolar components to have a different effect on the chromaticity.
- Beam decoherence and collective effects affect the tune.

The effect of optical errors has been estimated for the 2002 experiment. The rms beta-beating in SPS is around the 5% in both planes [5]. We have considered this realistic

Table 3: Percent deviation in the multipolar components arising from a low and realistic beta-beatings

	$\frac{\Delta\beta}{\beta}<1\%$	$\frac{\Delta\beta}{\beta}=5\%$		$\frac{\Delta\beta}{\beta}<1\%$	$\frac{\Delta\beta}{\beta}=5\%$
b3a	0.02	2	b5a	1.5	7
b3b	0.3	0.5	b5b	1.4	10
b4f	1.6	6	b6f	10	20
b4d	2.4	80	b6d	4	2

beta-beating plus a small beta-beating below 1% for comparison. These beta-beatings have been introduced in the model leading to the deviation in the different multipoles shown in Table 3. Sextupolar and decapolar components seem robust against optics errors. However the octupolar component b4d is severely affected by the 5% beta-beating. There is no clear scaling between the low and realistic beta-beating cases what might imply that there is an important random component. This should be addressed in the future by simulating a large number of machines with the same beta-beatings.

The beam at different momentum deviations has a different decoherence due to the fact that it experiences a different first and second order chromaticities (see [6] for example). The beam energy spread also plays an important role in the decoherence process. This has an effect on the measured tune. At high bunch charges (like for 2006) wakefields could also have an impact on the tune measurement. Multiparticle simulations using HEADTAIL have been performed to estimate these effects including a broad band resonator wakefield of 10 MΩ, see [7], and 1.1×10^{11}p. Fig. 4 shows the ideal tune versus dp/p used in the simulation the measured one from the beam centroid data and the fit to these data. The discrepancies of the chromatic terms between ideal and simulated are about 20%. Switching off the wakefields reduces this deviation to the 10% level. The source of this 10% deviation is the decoherence due to the first and second order chromaticities. To further reduce this error the energy spread should be reduced. Future experiments should be carried out using pencil beams with low charge and low energy spread.

To estimate the impact of this large error in the 2006 measurements two matchings have been done changing all the chromatic terms by +25% and -25%. The deviation of the multipolar components is summarized in Table 4. It is clear that the chromatic terms must be measured to better

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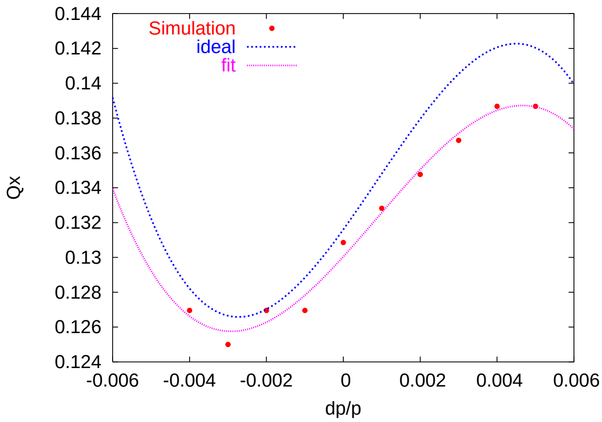

Figure 4: Multiparticle simulations of non-linear chromaticity measurement including a broad band resonator wakefield.

Table 4: Impact of the chromatic terms measurement error on the matched multipolar components for two cases: increasing all the measured chromatic terms by 25% and decreasing all of them by 25%

	2006 value	+25% [%]	-25% [%]
b3a	-0.000586	-47	45
b3b	-0.001283	23	-22
b4f	0.061	-30	46
b4d	-0.273	-27	81
b5a	9.2	-17	18
b5b	-11.8	-0.2	14

than 25%. Therefore these experiments should always be carried out at low intensity and possibly low energy spread, i.e. using pencil beams.

MEASUREMENT DURING THE RAMP

This section illustrates the results of a technical improvement achieved in 2006 that allows the measurement of the non-linear chromaticity along the SPS energy ramp. Orbit and tune data were acquired at different points of the ramp and for different momentum deviations. Different machine models have been constructed at all the ramp points based on the different known magnet parameters. The same matching as before was applied to all the ramp points yielding Fig. 5. Sextupolar and octupolar components seem to largely change during the ramp while the decapolar multipoles stay approximately constant. Note that the multipoles at the beginning of the ramp differ from those obtained at the injection of 26 GeV. This point should be studied in the future by measuring over a fraction of the injection plateau before the ramp starts.

CORRECTION OF NON-LINEAR CHROMATICITY

The primary motivation of these studies is the possibility of correcting non-linear chromaticity in the SPS, and

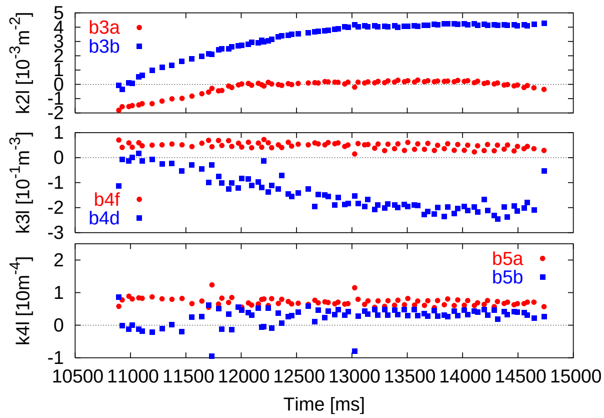

Figure 5: Measurement along the ramp in 2006.

later on, in the LHC. Once we have established the full non-linear model we can devise a configuration of the SPS non-linear elements that would compensate the non-linear chromaticity. The SPS is equipped with strong sextupoles and octupoles. This guarantees the correction of first and second order chromaticities. Third order chromaticity can be indirectly modified by combining large sextupoles and octupoles. A first attempt of this type of correction in 2006 failed due to technical problems with the magnets. This correction scheme will be further explored in future experiments.

CONCLUSION

There is a poor reproducibility of the SPS non-linear model from year to year due to differences in the cycle, the intensity and the dp/p range. Systematic errors arising from optics seem reasonable with the exception of the octupolar component b4d. On the other hand large systematic errors appear for large bunch charges and large energy spread, requiring future measurement to be carried out with pencil beams. Non-linear chromaticity correction is limited by the lack of decapoles in the SPS but more tests are required.

ACKNOWLEDGMENTS

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REFERENCES

[1] G. Arduini, et al., CERN SL Note 2001-030 MD; SL Note 2001-049 MD; and Proc. EPAC 2002, Paris, p. 1220.

[2] G. Arduini et al, Proc. PAC2003, Portland, p. 2240; and CERN AB Note 2003-025 (ABP) (2003).

[3] G. Arduini et al, PAC 2005, Knoxville, Tennessee; and CERN-AB-2005-037.

[4] http://mad.web.cern.ch/mad/

[5] J. Klem, SL seminar, http://cern.ch/SL-seminar/talks/SL.Seminar.jk.ps

[6] G. Rumolo et al, NIM-A, 528 (3), p.670-676, Aug 2004

[7] H. Burkhardt, et al, CERN Report No. SL-Note-2001-043 (MD), 2001.

