EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN – SL DIVISION

SL-Note-2002-041 OP

Dynamic Effects on Chromaticity for the LHC beam cycle in the SPS

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Abstract

During the energy ramp of the SPS the chromaticity is subject to significant dynamic effects. Sextupolar field errors due to eddy currents and remanent fields lead to beam momentum and ramp rate dependent corrections. Detailed measurements on the LHC beam cycle have been used to verify the modelling and reproducibility the chromaticity corrections. Large deviations were found between the presently used model and the measured chromaticity trims. An improved empirical model is suggested.

Geneva, Switzerland

December 20, 2002

1 Introduction

As injector for the LHC, the SPS must deliver very bright beams with high efficiency and without emittance degradation to both LHC rings. At the same time beams must also be provided to fixed target experiments and to the CNGS target. Consequently a larger number of different magnetic cycles must be setup, operated and maintained at the same time compared to the present situation. To speed up the setting up of the cycles, faster tune and chromaticity measurement procedures have been developed during the 2001/2002 SPS runs. The modelling of the dynamic effects on chromaticity in the ramp has been verified, and the stability of the chromaticity correction has been tracked over a period of 2 years.

In the first part of this note, the fast tune measurement principle is briefly described. The reference tune functions after correction and the required tune trims are given for the LHC cycles. Results for dynamic effects on the chromaticity are then presented and confronted with the presently used model for the chromaticity. An improved model is proposed. Finally sextupolar field errors in the dipoles are extracted from the new chromaticity data for the entire LHC cycle.

2 Fast Tune Measurements

At the SPS, standard tune measurements are performed by kicking the beam at a selected time in the cycle using dedicated tune kickers. For long ramp segments, a complete measurement and correction procedure can be very time consuming. In particular, no fast check of the tune function is possible with such a single point measurement procedure.

To provide faster response times for tune measurement, a continuous tune measurement (MULTIQ) system was developed in 1995/1996 for proton and lepton beams in the SPS [1]. The MULTIQ system relies on the transverse damper to excite beam oscillations. The excitation signal is added to the driving stage of the damper power amplifiers to avoid perturbing the good functioning of the damper system, which must always be available to fight transverse instabilities. The beam is excited by a *chirp* signal, a sine wave with a frequency increasing linearly with time over a certain range. The 20 msec long chirp sweep presently covers a fixed frequency range corresponding to tunes between 0.56 to 0.97. One chirp sweep can be sent every 30 msec, providing one tune point as shown in Figure 1. A maximum of 150 chirp sweeps (4.5 seconds) can be measured simultaneously during a single cycle, the limitation arising mainly from memory requirements for the data transfer (4.5 seconds correspond to $\sim$200 kturns). Obviously a sequence of chirps will inevitably increase the transverse beam emittance, but this point is not considered here since it is assumed that the measurements are not done on beams that will be delivered to the LHC. The stability of the SPS is high enough that a continuous measurement of each beam is not required.

The turn-by-turn beam oscillations induced by the chirps are recorded by the same BOSC system that is also used for the usual tune measurements using the kick method.

For a number of years the MULTIQ system was not used for protons due to the absence of analysis and correction feed-forward software. In 2001 new software providing online analysis of MULTIQ data sets became available. With this software it is possible to combine a number of data sets to reconstruct the tune for a full SPS cycle, to filter and edit the data... Furthermore the measured tune function can be used to feed-forward corrections for the entire cycle, thereby significantly reducing the time required to obtain a smooth tune dependence over a cycle. Tune

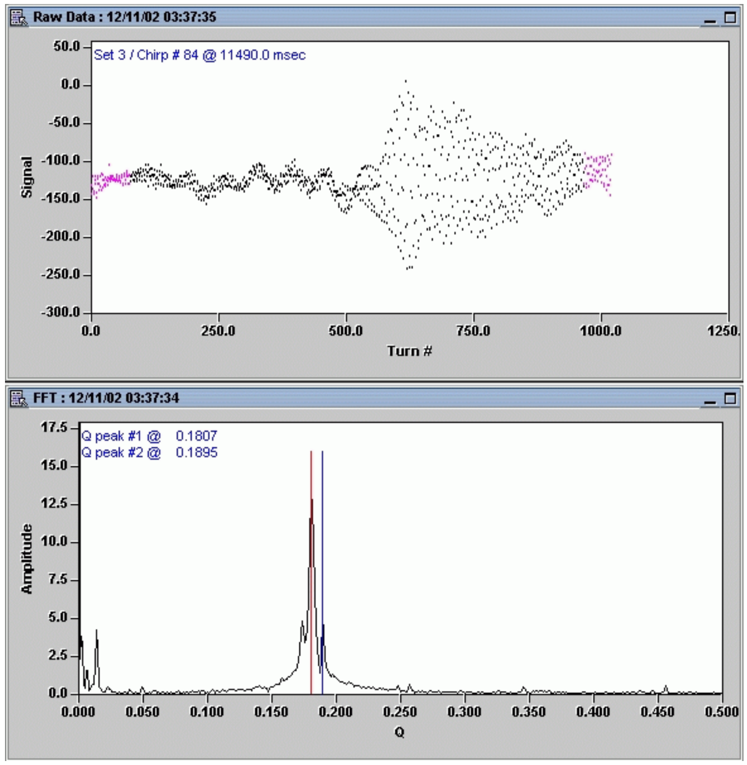


Figure 1: Online MULTIQ raw data display for one chirp sweep : horizontal beam position signal (top) and the corresponding FFT spectrum (bottom). The modulation of the horizontal tune by synchrotron motion is visible on the spectrum. Black dots on the top plots correspond to the duration of the chirp excitation.

corrections converge very rapidly for reasonably smooth tune fluctuations. Spikes require a more careful treatment. This measurement procedure is particularly well adapted to the long and smooth ramp of the LHC beam cycle (Figure 3). For the faster ramps of the fixed target beams, the granularity is not sufficient at the start of the ramp and around the transition to avoid the use of detailed measurements using the standard 'kicked beam' method.

In addition to the tune, it is possible to reconstruct the chromaticity in a cycle by comparing two tune data sets for the same cycle but measured for different radial steering (RF frequency) settings. This possibility opens the way for a fast chromaticity measurement over a complete SPS cycle.

3 SPS beam cycles

Data and machine settings from four SPS super-cycles are used in this note. Three cycles are used with LHC type beams (SC 537, 540 and 542) and one is used for fixed target operation (SC 950). The main parameters of the cycles are given in Table 1.

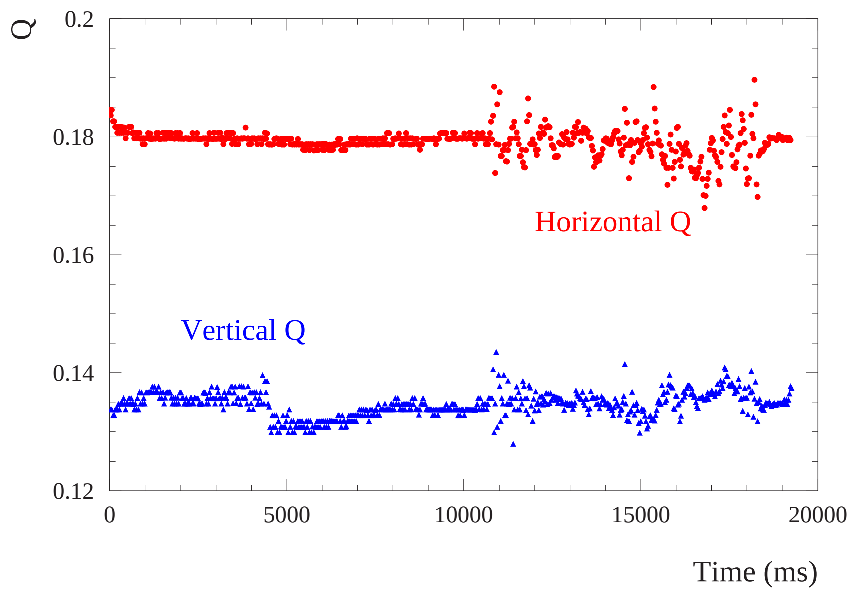


Figure 2: Tune evolution for the SPS super-cycle 540 (LHC beam), recorded with 12 bunches of nominal intensity ($\sim 10^{11}$ p/bunch) on September 26 2002. Four consecutive MULTIQ measurements are necessary to obtain the full information for each plane.

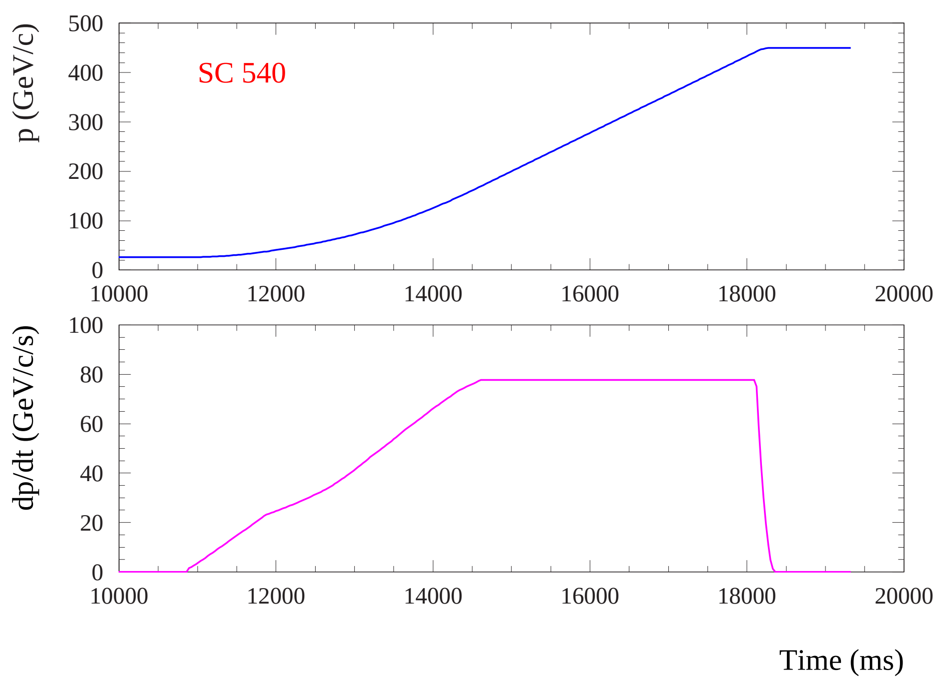


Figure 3: Evolution of the beam momentum (top) and the change of momentum $\dot{p}$ for the LHC cycle ramp.

Cycle No.	Beam type	Momentum (GeV/c)		Ramp segment
		Injection	Flat top	length (s)
537	LHC	26	450	7.5
540	LHC	26	450	7.5
542	LHC	26	80	2.4
950	Fixed Target	14	400	3

Table 1: Parameters of SPS super-cycles referenced in this note. Super-cycles 537 and 540 are identical except that cycle No. 537 was used in 2001, while cycle No. 540 was used in 2002. The ramp of SC 540 is displayed in Figure 3.

4 Tune evolution in the ramp

The primary goal of the MULTIQ system is to provide a fast and detailed measurement of the tune in a cycle. The measured reference tune evolution for LHC beams (SC 540) is shown in Figure 2 after corrections. The nominal tunes are $Q_h = 26.18$ and $Q_v = 26.135$. The fluctuations of the tune around the nominal values are maintained within an acceptable window of ± 0.01. Most fluctuations are in the form of short spikes. The energy ramp of this cycle is displayed in Figure 3.

To understand the trims that are required to obtain the tune dependence shown in Figure 2, the quadrupole strengths have been reconstructed from the current in the QD and QF quadrupole chains for the entire cycle using the calibration curves of the magnets. It is not possible to use directly the trim history because of inconsistencies arising from the history of the settings which are regularly copied from an existing cycle to a new one without a consistent treatment of all the trims. From the reconstructed strengths, it is possible to determine to total tune trim that had to be applied on top of the nominal machine settings to obtain the smooth tune measurement of Figure 2. The reconstructed tune trims ΔQ_{Trim} are shown in Figure 4 as a function of the time in the cycle as well as against beam momentum. The start of the ramp and the saturation in the magnets around 400 GeV/c are the areas where the largest corrections a required. At injection the relative size of trims does not exceed 0.1%. The largest corrections in this cycle reach ± 0.5%.

The tune evolution varies little over the duration of an SPS run, requiring only minor re-adjustments from time to time.

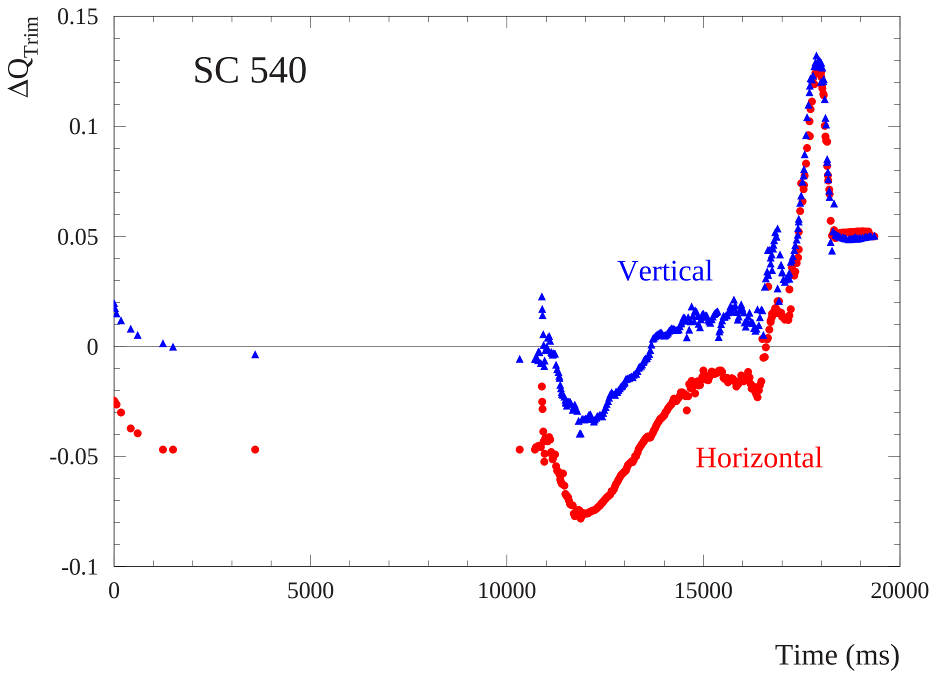
5 Chromaticity evolution in the ramp

In this note we use the standard SPS definition of the (normalized) chromaticity given by

$$\xi_u = \frac{Q'_u}{Q_u} = \frac{\Delta Q_u}{Q_u \, \Delta p/p} \tag{1}$$

with Q_u the machine tune and p the beam momentum. The horizontal and vertical planes are labelled by u. Q'_u is the LEP/LHC definition for the chromaticity. The lattice quadrupoles of the SPS give a contribution to the chromaticity in each plane of

$$\xi_u^Q = -1.257 \tag{2}$$



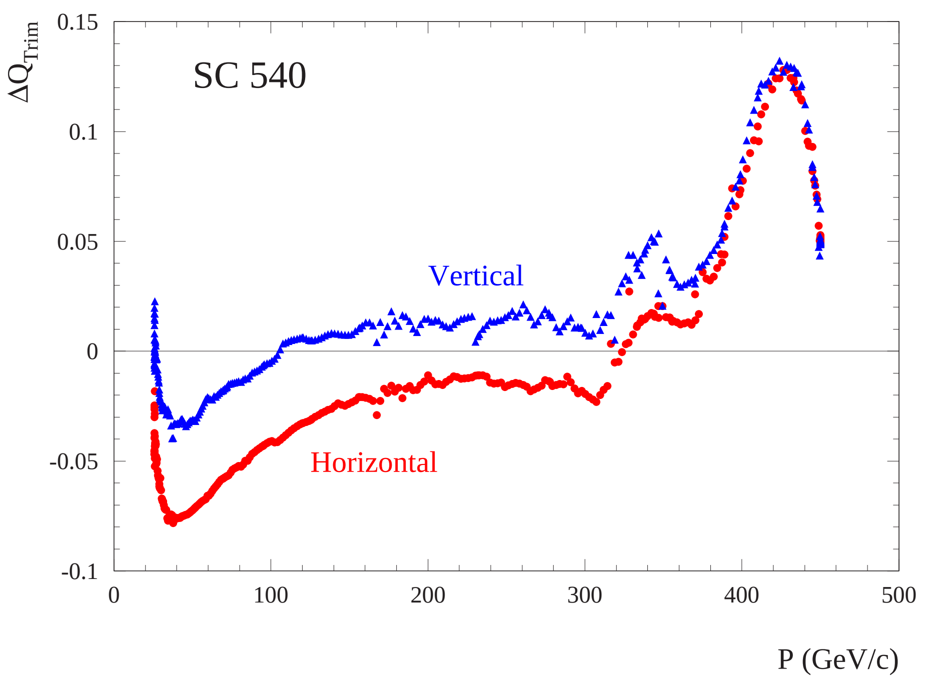


Figure 4: Total tune trim required to obtain the tune functions shown in Figure 2. The trims are relative to the nominal setting for the selected optics and reference tunes. Top : tune trim versus time in the cycle. Bottom : tune trim versus beam momentum. The saturation effects in the magnets starting around 350 GeV/c are clearly visible. The decay of the field in the dipoles at the beginning of the injection plateau is visible from the slowly varying tune trims up to 1000 ms.

corresponding to $Q'_u = -32.9$ for LHC beam tunes of $Q_u = 26.15$.

The chromaticity is corrected in the SPS using 108 lattice sextupoles, 54 LSD (vertical focusing) and 54 LSF (horizontal focusing) magnets. The LSD magnets are grouped in 2 families, LSDA (18 magnets) and LSDB (36 magnets). The LSF are grouped in 3 families, LSFA (24 magnets), LSFB (18 magnets) and LSFC (12 magnets). For the super-cycles and optics considered for this note, the strengths of LSFA and LSFC families are always identical. The total number of lattice quadrupoles is 216, i.e. there is only one sextupole for 2 quadrupoles.

At any given time during the SPS run, the total chromaticity trims can be reconstructed directly from the currents in the LSD and LSF sextupoles. The sextupole strength K_2 is given by

$$K_2[\mathrm{m}^{-3}] = \frac{1}{p[\mathrm{GeV/c}]} \left\{ \begin{array}{c} 0.67098 \\ 0.25940 \end{array} \right\} I[\mathrm{A}] \text{ for} \left\{ \begin{array}{c} \mathrm{LSF} \\ \mathrm{LSD} \end{array} \right\} \text{magnets} \tag{3}$$

where I is the sextupole current. The linear relation is valid up to currents of 250 A for LSD and up to 300 A for LSF sextupoles, which covers the entire range of interest. The analysis that follows obviously relies on the accuracy of the sextupole calibration tables.

Of particular interest is the chromaticity trim reconstructed at the time corresponding to a chromaticity measurement. The reconstructed chromaticity trims $\Delta\xi_u^{\mathrm{Trim}}$ for the standard LHC cycles (SC 537 and 540) are displayed in Figure 5 without the expected contribution due to ξ_u^Q. The data for SC 537 (used in 2001) and SC 540 (used in 2002) have been averaged, and the results are consistent. Differences are indicated by error bar on the plots. The trims are clearly very large.

Already in the design phase of the SPS, contributions to the chromaticity due to sextupolar field components from dipole magnets (remanent fields and saturation) and eddy currents on the vacuum chamber had been identified and evaluated [2]. During SPS commissioning the parameters of the model were determined experimentally from chromaticity measurements [3]. The model used for those additional contributions (excluding the contribution due to ξ_u^Q) is based on 3 terms given by

$$\Delta\xi_u^{\mathrm{ind}} = a + \frac{b}{p} + c\,\frac{\dot{p}}{p} \tag{4}$$

where the first two terms are due to sextupolar field components in the dipole magnets (one term proportional to the dipole field and a constant term due to remanent fields). The last component represents the effects of vacuum chamber eddy currents induced by the field changes during the ramp. References [2] and [3] used an alternative representation where parameter b is replaced by $b = b'\ p_{inj}$, with p_{inj} the momentum at injection. The default parameter values used in the past years for machine settings generation, are given in Table 2, column 2. The values determined in Ref. [3] for cycles with maximum momentum of 200 GeV/c are given in column 3 of the same table.

The induced chromaticity $\Delta\xi_u^{\mathrm{ind}}$ reconstructed from the trims for super-cycles 537 and 540 are compared to the model expectation in Figure 6 (dashed line). $\Delta\xi_u^{\mathrm{ind}}$ is obtained from $\Delta\xi_u^{\mathrm{Trim}}$ by subtracting the measured chromaticity ξ_u^{meas} and by inverting the sign, $\Delta\xi_u^{\mathrm{ind}} = -(\Delta\xi_u^{\mathrm{Trim}} - \xi_u^{\mathrm{meas}})$. For super-cycles 537 and 540, $\xi_u^{\mathrm{meas}} = 0.075 \pm 0.025$. With the exception of the injection plateau, the measurements differ significantly from the model. In particular the change at the beginning of the ramp is approximately a factor 2 larger for the data than for the model. Furthermore, the *dip* (or *peak*) between 100 and 450 GeV/c (14000 to 19000 ms) cannot be described by the limited number of parameters of the model.

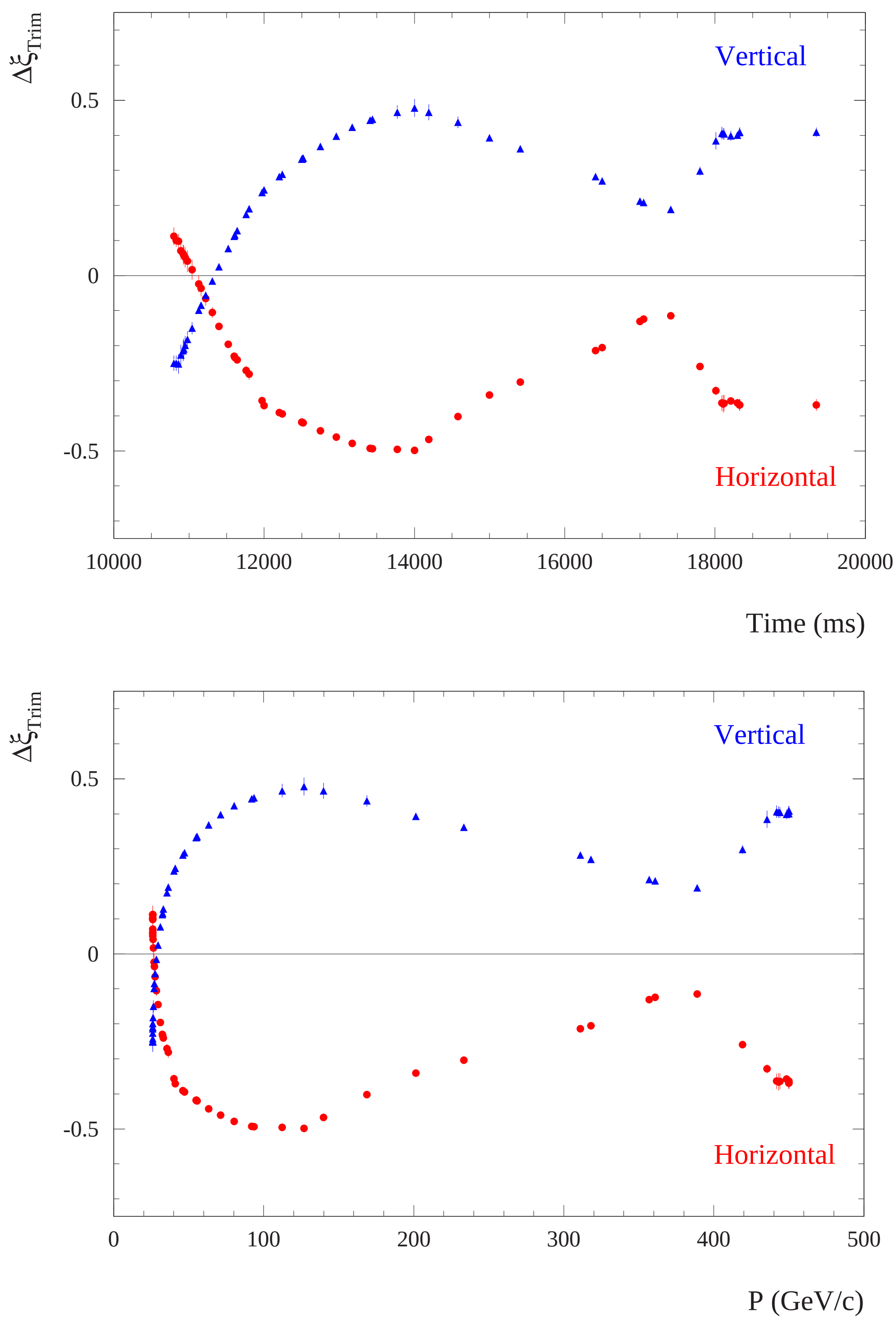
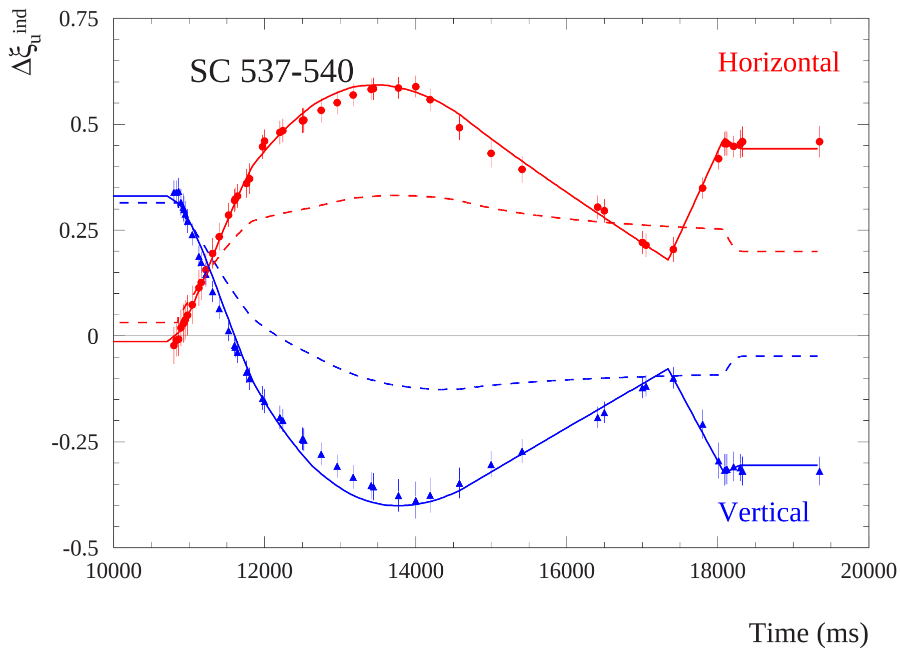


Figure 5: Average chromaticity trims $\Delta\xi_u^{\rm Trim}$ applied to the LHC beam cycles (SC 537 and 540) to obtain a chromaticity for the beams of $\xi_u = 0.075 \pm 0.025$. The contribution due to ξ_u^Q is not included $\Delta\xi_u^{\rm Trim}$. Top : chromaticity trims versus time in the cycle. Bottom : chromaticity trims versus beam momentum. Error bars indicate the spread between the two cycles.



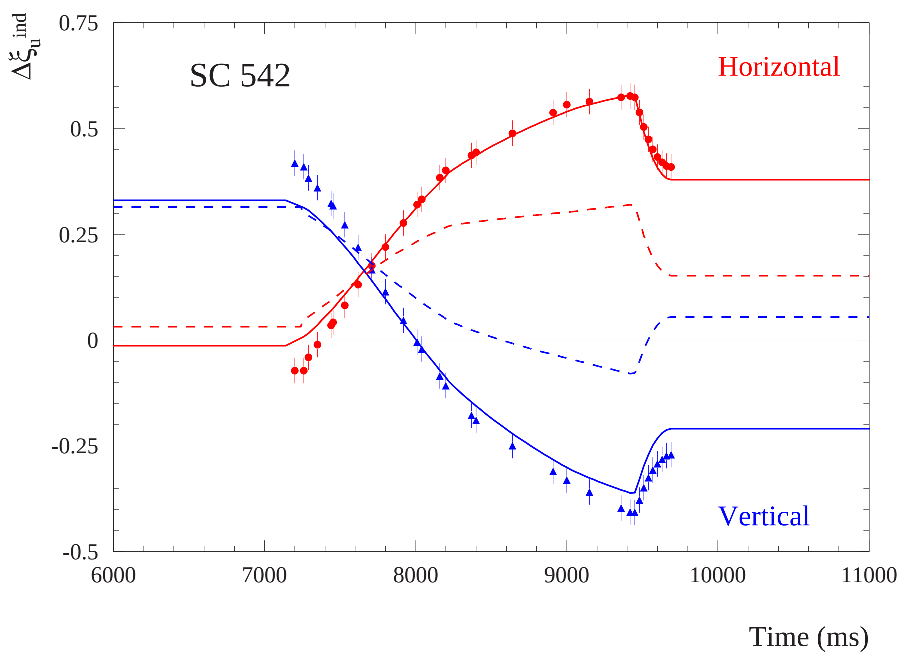


Figure 6: Dependence of $\Delta\xi_u^{\rm ind}$ on the time in the cycle for SC 537 and 540 (averaged, top plot) and for SC 542 (bottom plot). Points represent the values reconstructed from the trims and measurements. The dashed line corresponds to the default model with the parameters of column 1 of Table 2. The solid line is the fit to the new model with parameters in column 3 of Table 2.

Parameter	Horizontal Plane Model					
	Default	Commis.	New /LHC		New /FT	
a	0.21	0.35	0.61	± 0.02	0.54	± 0.02
b (GeV/c)	-4.63	-11	-16.2	± 0.6	-13.3	± 0.5
c (1/s)	0.30	0.38	0.36	± 0.03	0.36	
p_1 (GeV/c)	-	-	60	± 20	60	
p_2 (GeV/c)	-	-	385	± 10	385	
d	-	-	-0.46	± 0.03	-0.46	
e	-	-	0.33	± 0.02	0.33	

Parameter	Vertical Plane Model					
	Default	Commis.	New / LHC		New /FT	
a	-0.07	-0.13	-0.52	± 0.02	-0.55	± 0.02
b (GeV/c)	10.0	9.5	22.0	± 0.6	20.0	± 0.5
c (1/s)	-0.28	-0.30	-0.29	± 0.03	-0.29	
p_1 (GeV/c)	-	-	60	± 20	60	
p_2 (GeV/c)	-	-	385	± 10	385	
d	-	-	0.44	± 0.03	0.44	
e	-	-	-0.28	± 0.02	-0.28	

Table 2: Chromaticity model parameters for the horizontal (top) and vertical (bottom) planes. The parameters for the default model used for settings generation (3 parameters) are given in Column 2. Results from the first measurements [3] are given in column 3 ('Commis.') for $p_{inj} = 10$ GeV/c (Reference [3] used the parameterization $b' p_{inj}$ instead of b). The fitted parameters for the new model (7 parameters) are given in the 3 column for the LHC beam cycle. The last column holds the parameters for the new model with parameters a and b readjusted to better match the fixed target cycle.

An new empirical model, that provides a better description of the data, in particular for the dip between 100 and 450 GeV/c, is described by the following relation

$$\Delta\xi_u^{\rm ind} = a + \frac{b}{p} + c\,\frac{\dot{p}}{p} + \left\{ \begin{array}{c} - \\ d\,(p-p_1)/(p_2-p_1) \\ d + e\,(p-p_2)/(450[\mathrm{GeV/c}]-p_2) \end{array} \right\} \quad \left\{ \begin{array}{c} p \le p_1 \\ p_1 < p \le p_2 \\ p > p_2 \end{array} \right\} \tag{5}$$

where two new parameters d and e have been added to the initial model. Two *cut-off* momenta, p_1 and p_2, are also introduced. The parameters of this model were adjusted using a χ^2 fit on the data from super-cycles 537, 540 and 542 (see Table 1). The fit results are given in Table 2. With the additional 4 new parameters it is possible to describe more closely the observed chromaticity variations, in particular in the region between 100 and 450 GeV/c, see Figure 6 (solid line). While the agreement is rather good for the two cycles to 450 GeV/c, there are significant deviations between data and model for the special cycle 542 to 80 GeV/c. This seems to indicate some dependence of parameter b on the maximum field of the cycle (and in particular on the dipole saturation above 350 GeV/c). Fitting only data of SC 542 yields a somewhat smaller value for b of 14 GeV/c for the vertical plane and a better agreement data-fit for this cycle.

The fit to the new model shows that the contribution from the eddy current (c) is entirely consistent with the earlier results. Parameter b, which controls the slope of the chromaticity change in the first part of the ramp, is significantly increased. Large difference are also observed for parameter a, which is largely correlated to b. The structure (*dip,peak*) between 100 and 450 GeV/c, which is probably due to the field quality of the dipoles, can be reasonably well described by the new model. It is interesting to note that a contribution to the chromaticity due to the dipole magnet saturation, proportional to $(p - 340 \text{ GeV/c})$ for $p > 340$ GeV/c , was anticipated in Ref. [2].

The chromaticity for the fixed target cycle, with a much faster slope of the ramp, is compared with the model in Figure 7. Only data for cycle times larger than 1500 ms is accurate. Above 1400 ms data and model (determined using the data from the LHC cycles) agree rather well. At injection the difference is large, another indication of the possible dependence of the remanent field effects (b) on injection and flat top momentum. To improve the understanding at low fields, more precise data with different cycles types is required.

6 Sextupolar field errors of the SPS dipoles

A model of the SPS including field errors was set up by A. Faus-Golfe [4] to describe non-linear chromaticity and detuning with amplitude in the SPS as measured at 26 GeV/c. The model includes sextupole and decapole field errors inserted into the middle of each dipole and octupole field errors inserted into each quadrupole. Distinct field errors, labelled a and b, are introduced for the MBA and MBB dipoles due to the different chamber geometries.

In this SPS model, the integrated strength K_2L of the sextupolar field error (corresponding to the MULTIPOLE element of MAD [5]) is defined by

$$K_2L = \frac{L}{B\rho}\frac{\partial^2 B_y}{\partial x^2} \tag{6}$$

where L is the length of the dipole magnet and $B\rho$ the magnetic rigidity. Chromaticity changes $\Delta Q'_h$ and sextupolar field strength changes ΔK_2L are related by

$$\begin{pmatrix} \Delta Q'_h \\ \Delta Q'_v \end{pmatrix} = \begin{pmatrix} 5.10 & 1.89 \\ -2.32 & -3.89 \end{pmatrix} \begin{pmatrix} \Delta K_2^a L \\ \Delta K_2^b L \end{pmatrix} \tag{7}$$

where $K_2^a L$ and $K_2^b L$ are given in 10^{-3} m^{-2}. The inverse relation is

$$\begin{pmatrix} \Delta K_2^a L \\ \Delta K_2^b L \end{pmatrix} = \begin{pmatrix} 0.252 & 0.122 \\ -0.150 & -0.330 \end{pmatrix} \begin{pmatrix} \Delta Q'_h \\ \Delta Q'_v \end{pmatrix} \tag{8}$$

An error on the chromaticity $\Delta Q'_u$ of 1 unit in each plane, or equivalently an error on $\Delta\xi_u$ of 0.04, induces an error of $\sim 0.3 - 0.4\,10^{-3}$ on K_2L.

The measured chromaticity trims presented in the previous section can be converted into field errors using the relations given above. Figure 8 shows the field error strengths for the MBA and MBB dipoles as a function of the beam momentum for the standard LHC beam cycle. At 26 GeV/c the field error strengths are

$$K_2^a L = 0.8 \pm 0.3\ [10^{-3}\mathrm{m}^{-2}] \qquad \text{and} \qquad K_2^b L = -2.7 \pm 0.3\ [10^{-3}\mathrm{m}^{-2}]\ , \tag{9}$$

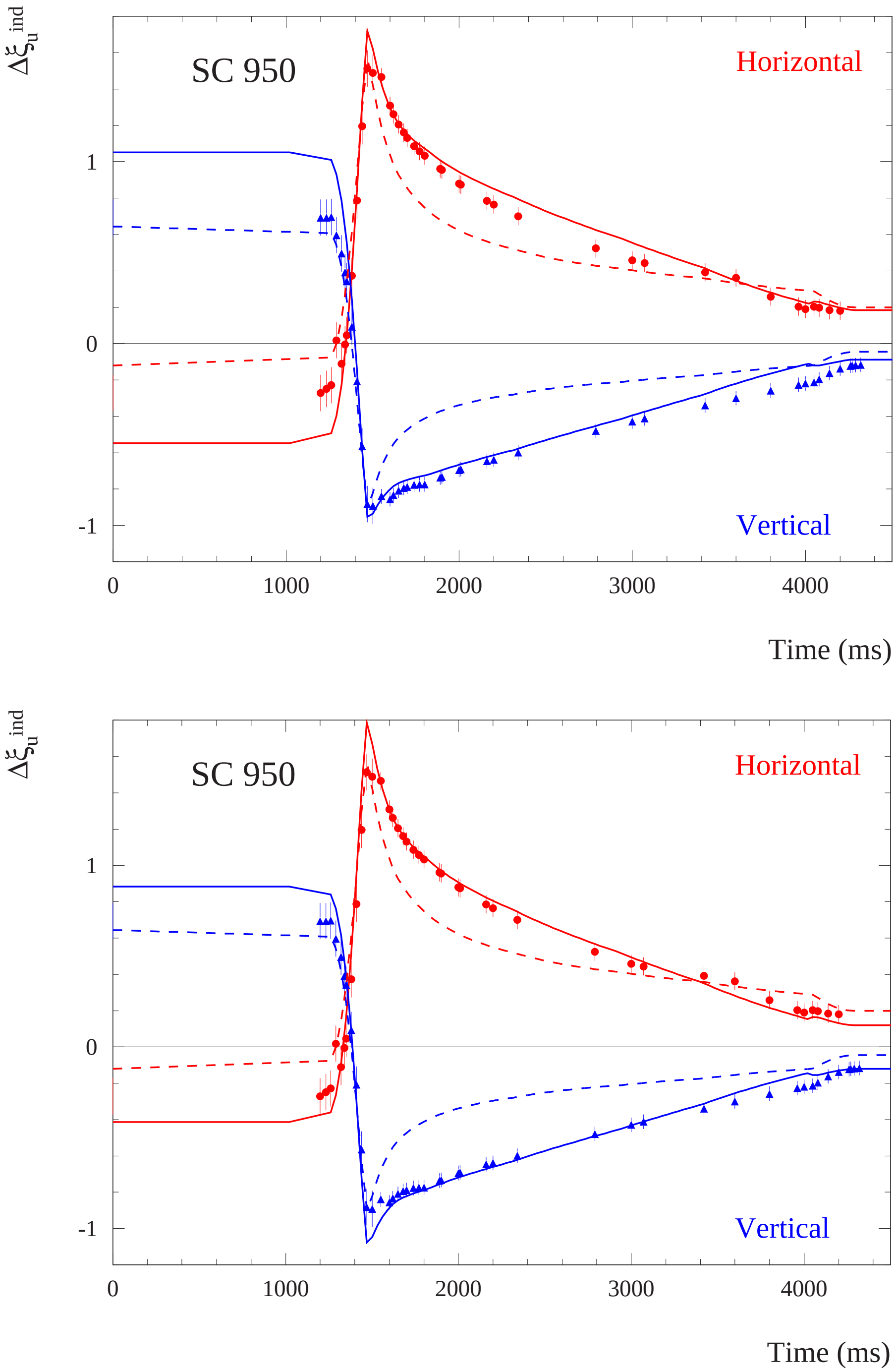


Figure 7: Dependence of $\Delta\xi_u^{\text{ind}}$ on the time in the cycle for super-cycle 950. Points represent the values reconstructed from trims and measurements. Accurate data is only available for cycle times above 1550 ms. The dashed line corresponds to the default model with parameters given in column 2 of Table 2. Top: the solid line is the prediction of the new model fitted using only the LHC beam cycle data (column 4 in Table 2). Bottom : the solid line is the prediction of the new model where parameters a and b have been allowed to vary with respect to the top plot (column 5 in Table 2).

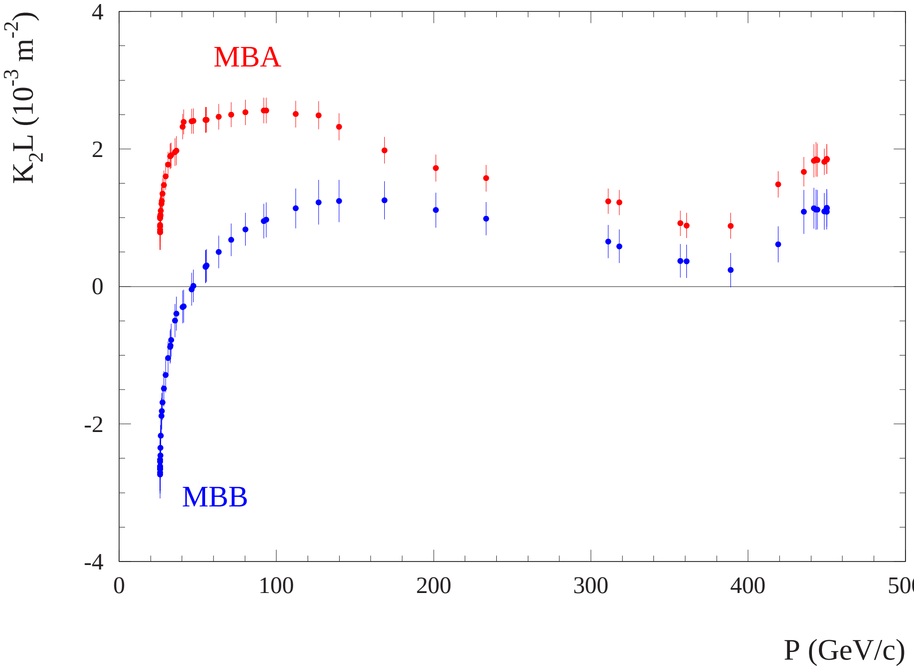


Figure 8: Strength of the sextupolar field components in the main SPS dipoles MBA and MBB as a function of the beam momentum. The data is averaged for SC 537 ad 540 and includes the contributions from eddy currents.

in agreement with the results quoted in Ref. [4] where the various measurements yielded values ranging between 0.75 and 1.7 for $K_2^a L$ and between -0.8 and -3.6 for $K_2^b L$ (all values in $10^{-3}\mathrm{m}^{-2}$). It must also be noted that the later results were obtained for a different magnetic cycle.

The strength $K_2 L$ can be converted into a normalized LHC field error b_3 (in units of 10^{-4}) [6] using the relation

$$b_3 = \frac{(K_2 L)\,\rho\,R_{ref}^2\,10^4}{2L} = 0.17\,(K_2 L)[10^{-3}\mathrm{m}^{-2}] \tag{10}$$

with $\rho = 741$ (m) the SPS bending radius, $L = 6.26$ (m) the SPS dipole length and $R_{ref} = 17$ (mm) the LHC reference radius for field errors in the main dipoles. The observed field errors in the SPS correspond to a maximum of $\sim \pm 0.4 - 0.5$ units of b_3 using the LHC definition and reference radius. The full variation over one LHC beam cycle in the SPS is $|\Delta b_3| \sim 1$ unit, to be compared with an expected change of ~ 3 units in the LHC (decay at injection and snapback) [7].

7 Conclusion

Detailed chromaticity measurements have been performed on 3 different LHC beam cycles in the SPS during the 2001 and 2002 runs. The data reveals that the model used presently to generate machine settings for chromaticity has a poor accuracy for this cycle and can be improved significantly. The chromaticity trims are stable over 2 runs and do not require frequent readjustments. The updated model is not able to correctly describe the chromaticity for the entire fixed target cycle, indicating that at low field the dependence of the overall cycle parameters is more complex. Measurements on a larger number of cycles are required to pin down the correlations more accurately.

The strength of the sextupolar field error in the main dipoles have been reconstructed from the measured chromaticity and machine settings for the LHC cycle. The integrated strengths vary between -2.7 and $+2.5\ 10^{-3}\mathrm{m}^{-2}$ over the cycle.

8 Acknowledgements

Lars Jensen provided invaluable help with the MULTIQ system, while Angeles Faus-Golfe was kind enough to provide me with her SPS model including field errors.

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