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Dipole Field, Tune and Chromaticity Correction at the SPS : from Converter Tracking to Eddy Currents

C. Arimatea, D. Jacquet, L. Normann, J. Wenninger

Abstract

Good control of key parameters like dipole field, tune and chromaticity is a basic requirement for fast cycle commissioning and for good beam transmission through the SPS ramp. The reproducibility of those parameters depends on power converter tracking, eddy currents and remnant fields. The new SPS control system was used to study some of the problems in the low energy ramp segment of the fixed target beam. A small modification of the function generation for the main converters is shown to reduce residual converter tracking errors by more than one order of magnitude. Tune and chromaticity corrections have been analyzed and summarized for different cycles, both for the ramp as well for the injection plateau where eddy current may play a significant role.

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1 Introduction

In the area of LHC and CNGS operation the SPS must be a flexible multi-cycling machine. A large number of different cycle combination must potentially be setup, operated and maintained at the same time compared to the past situation. For this reason the SPS control system was renovated in 2006 and the new LSA control system was used successfully for the first time on a large scale. It resulted in a record number of commissioned and operated SPS super-cycles. The increased flexibility of this new control system also eased tests to improve for example the shape and speed of the SPS ramps.

A recurrent observation in 2006 was the fact that once a given cycle was tuned, a copy of the same cycle inserted into another super-cycle did not give the same performance, and could result in significant beam loss (up to 80%). Such differences are only observed on fixed target (FT) beam ramps that have a more abrupt start than the smooth LHC ramps. Furthermore the differences seem to occur almost exclusively in the first 400 ms of the FT ramps, i.e. before and slightly after transition. Tests were performed at the end of the run in 2006 to understand this effect and improve the situation from the point of view of the power converter tracking.

This note is the continuation of a series of documents aimed at a better and more systematic understanding of the central SPS parameters that are the main dipole field [1, 2], the tune and the linear chromaticity [3] to improve setting up and the generation of machine settings. This note presents measurements and tests that have been performed on the control of the SPS main power converters in order to understand such problems and possibly cure or at least improve them in 2007. An analysis was also performed to get a better insight of the reproducibility of the tune corrections as a function of the beam momentum and to study eddy current effect at injection. Finally the chromaticity corrections obtained in 2006 are compared with earlier data [3].

2 Tracking of the SPS main converters

The ramp functions for the SPS main power converters, the main dipole circuit (MB) and the three lattice quadrupole circuits (QF1,QF2 and QD), are generated by a special application designated as *Settings Generation*. For the four main circuits the ramp is decomposed into segments of 30 ms or of integer multiples of 30 ms. The resulting converter reference function has points spaced by $n \times 30$ ms, $n \geq 1$. This **30 ms step rule** was established many years ago.

The shape of the ramp depends on the beam type. Fixed Target (FT) type beams that are used for the SPS Fixed Target program and for CNGS have a fast 3 second long ramp from 14 to 400 GeV/c. The standard LHC beam ramp from 26 to 450 GeV/c is slower and lasts 7.5 seconds. A faster LHC ramp with a length of 4.2 seconds was also tested successfully in 2006. The momentum derivative dP/dt for standard FT and LHC ramps is shown in Figure 1. The fast cubic acceleration at the beginning at the FT ramp, with $P \sim t^3$, is clearly visible. The slower LHC ramp is mostly parabolic or linear.

The main power converter regulation is not able to reproduce perfectly the current that is required by the nominal ramps, in particular in ramp sections with fast changes of the derivative. To compensate for a constant lag during ramp sections the converter function is advanced by 1 ms when it is sent to the converter control system. The current error $\Delta I_{PC} = I_{meas} - I_{nom}$, where I_{meas} is the measured current and I_{nom} the nominal current is shown in Figure 2

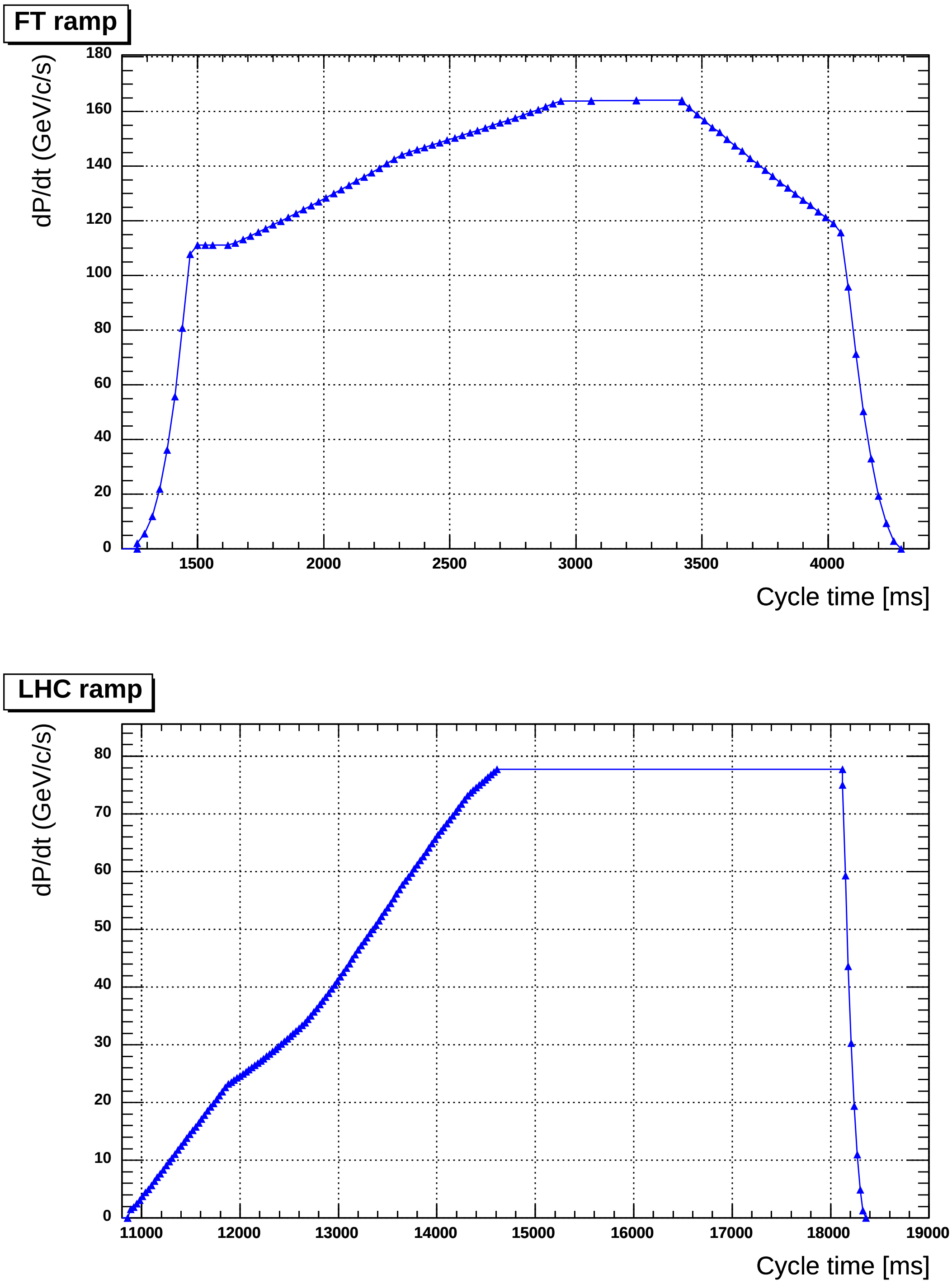

Figure 1: Momentum derivative dP/dt for the standard Fixed Target (top) and LHC (bottom) ramps. Note the differences in the vertical scales for the two plots.

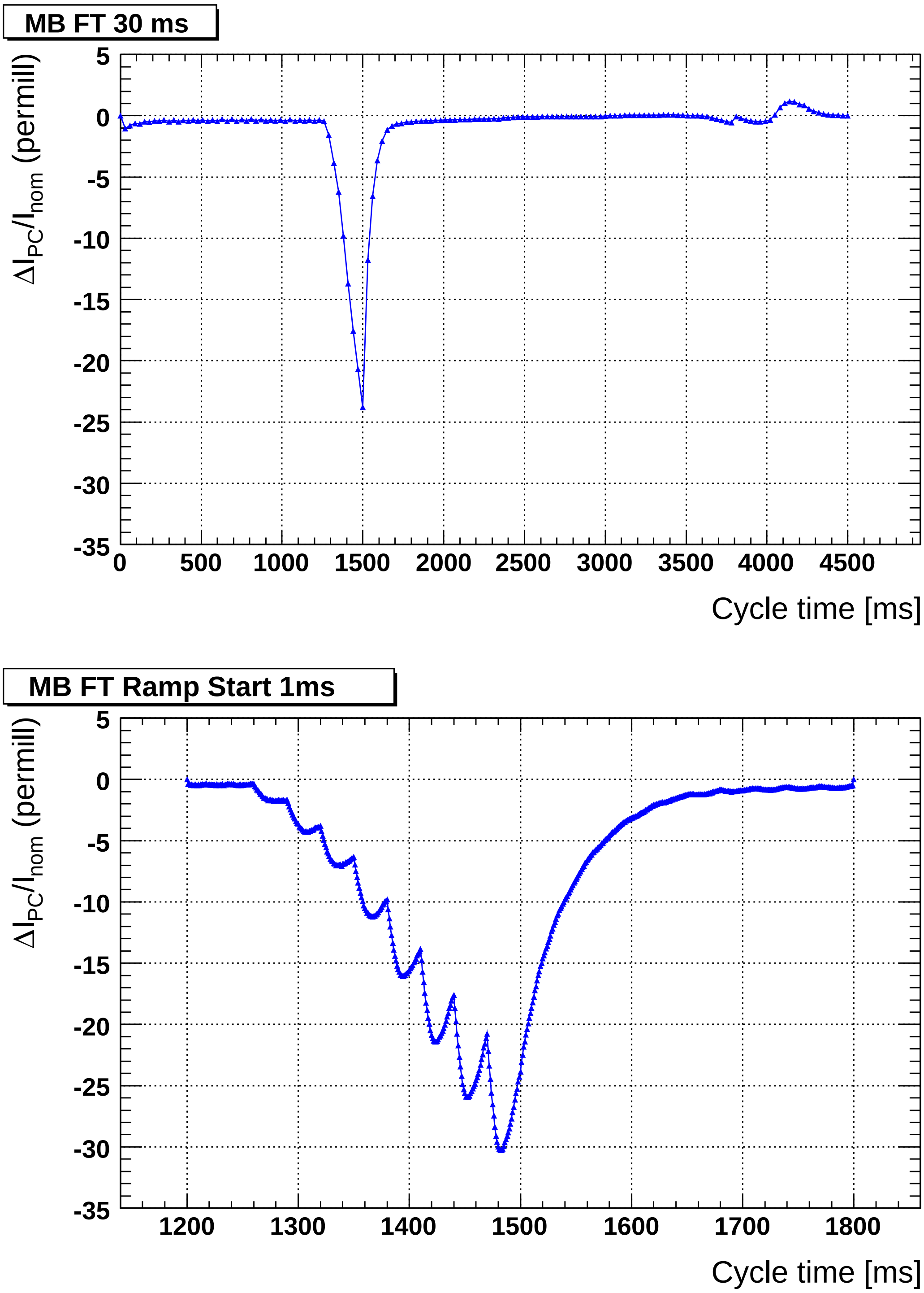

Figure 2: SPS Main Bends current error measured in 30 ms intervals over the entire cycle (top) and over 1 ms intervals on the start of the ramp (bottom). The data corresponds to the standard FT ramp.

(relative to I_{nom}). The relative current deviations can reach several percents and are particularly pronounced at the start of the ramp due to the smaller I_{nom}. A detailed measurement with 1 ms steps of the ramp start reveals small lobes spaced by 30 ms on top of a smooth current error.

There is a simple explanation for the those 'lobes': the converter is not able to follow the linear ramp segments but rather performs a smooth interpolation of the current between consecutive points of the function, see Figure 3. This also explains the sign of the error which is due to the positive second derivative of the current.

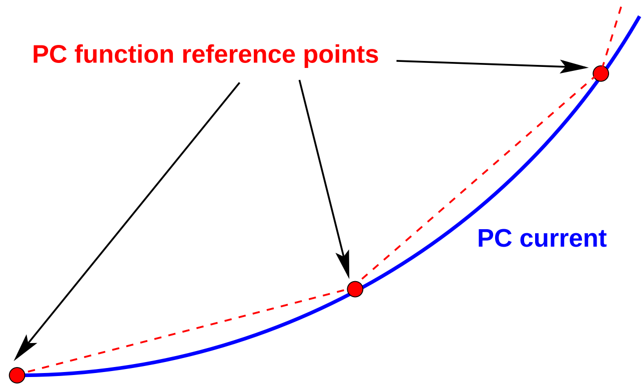

Figure 3: Origin of the current error visible in Figures 2 and 4. The converter regulation performs a smooth interpolation between the reference points.

The standard technique to compensate for those errors, designated as *Autotrim*, is to measure the error ΔI_{PC} at intervals of 30 ms and to add the error as a correction to the function that is sent to the converter. In other words the reference function of the converter is no longer $I_{ref}(t) = I_{nom}(t + 1\ \mathrm{ms})$ but

$$I_{ref}(t) = I_{nom}(t + 1\ \mathrm{ms}) - \Delta I_{PC}(t) \tag{1}$$

This procedure is iterated and it converges well even for fast ramp segments provided the correction ΔI_{PC} is evaluated at fixed intervals of 30 ms that coincide with the points of the reference function. After *Autotrim* I_{meas} and I_{nom} usually agree with good accuracy (< 0.1 A) at the points spaced by 30 ms that are used for the procedure. Attempts to correct the error more accurately, for example at closer time intervals, result in diverging corrections and large current oscillations of the converters, because the converters cannot follow the linear ramp segments. The residual error on the current ΔI_{PC} is shown in Figure 4 for the start of the FT ramp. Large oscillations are still present between the 30 ms reference points. Fortunately the relative errors are almost identical for the main dipole and quadrupole circuits: to first order the tune of the machine is not affected too much. Note that a 1% error on the tune corresponds to $\Delta Q = 0.26$, which is intolerable for beam operation where $\Delta Q \leq 0.01$ is required. The same residual error is negligible for the slow LHC ramp. While the tune error after *Autotrim* on the LHC ramps is smooth and rather easy to correct, the tune errors on the FT ramp tend to exhibit fast changes over very short time intervals and are difficult to correct in the region between 1200 and 1600 ms, which corresponds to the region with the large tracking errors. In addition the tunes are not always reproducible, i.e. frequent adjustments are required, in particular after a

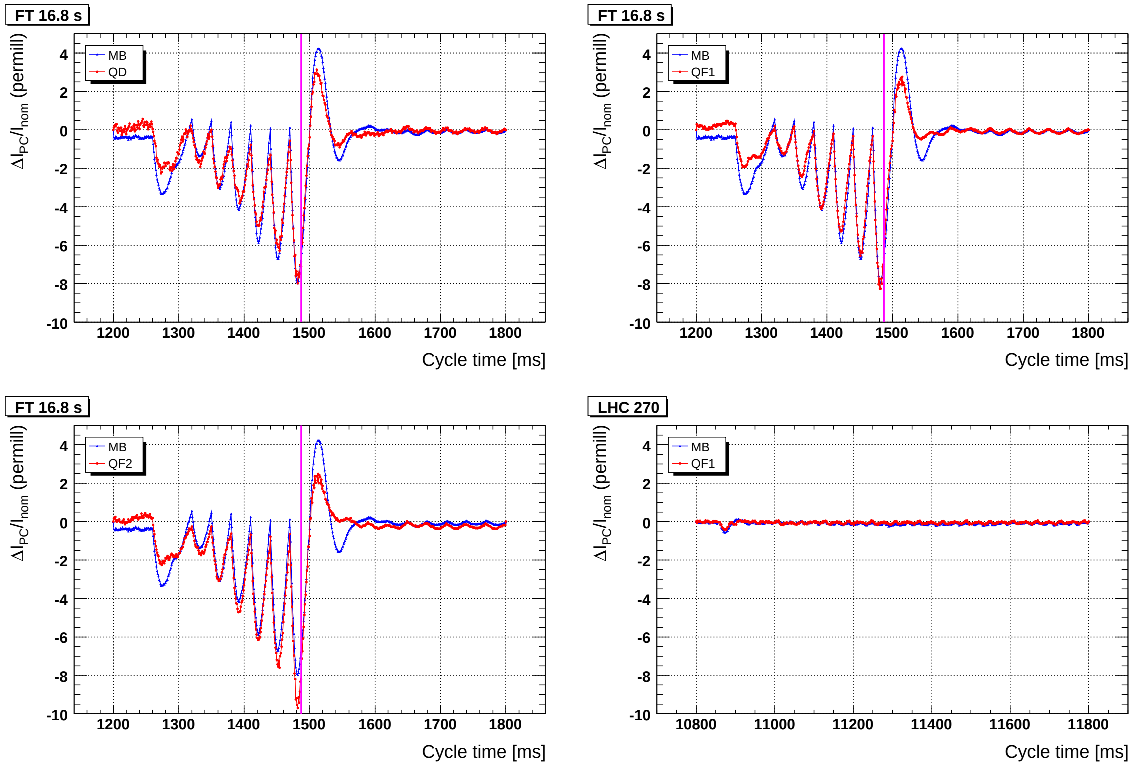

Figure 4: Residual relative current errors after *Autotrim* for the SPS main converters, measured in 1 ms intervals at the start of the FT ramp (top and bottom left) and at the start of the nominal LHC ramp (bottom right). In all cases the error of the main bends is compared to the error of the quadrupole circuits. The vertical line (magenta) indicates the moment of transition.

stop (due to longer access or MD) or for a new cycle. It is not unreasonable to assume there is a correlation between the rather poor tracking and the tune adjustment issues for FT beams. An additional problem may arise if trims are performed at points that do not correspond to the 30 ms steps, which can easily occur.

2.1 Ramp Generation Improvements

The residual errors that are visible in Figure 4 cannot be corrected by the *Autotrim* procedure, i.e. by feeding back the measured error to the PC reference function. Attempt to do so result in large oscillating current errors. The origin of the 30 ms spacing is found in the history of the converter regulation and control. The initial regulation system had fixed 30 ms intervals, and when the Mugef ramp cards where introduced, the available memory limited the spacing to 30 ms. With time the 30 ms spacing has become engraved in the control systems and was not questioned for proton beams (5 ms point spacing was used for the short lepton beam ramps).

The 30 ms structure present on the converter current error is pointing towards the actual reference function as being at the origin of the problems. In fact from Figure 3 it follows that an obvious cure consists in a reduction of the point spacing since the former limitations no longer apply. Advantage was taken of the flexible new SPS control system to study those errors in

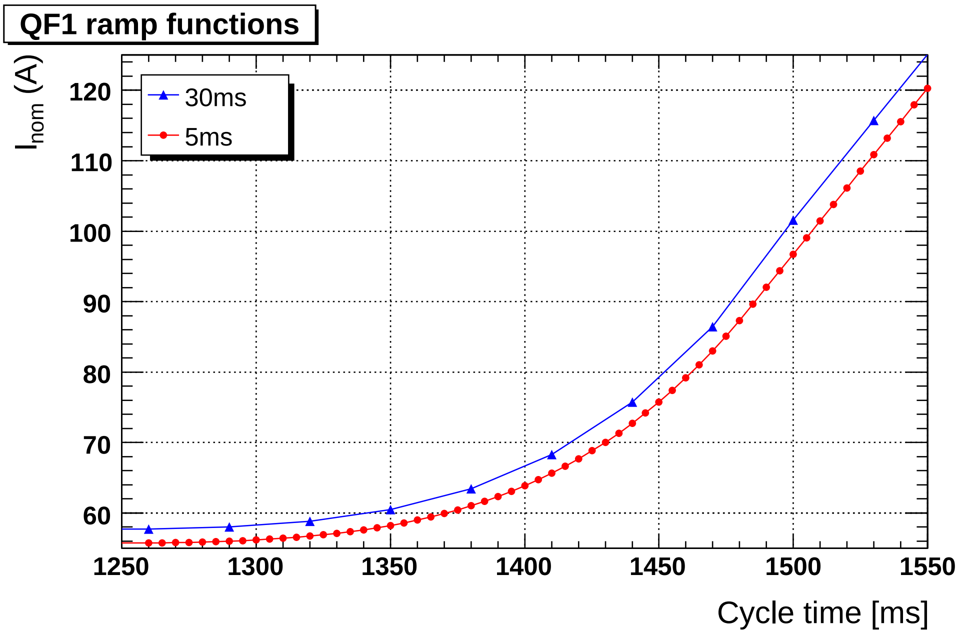

Figure 5: Comparison of the nominal ramp functions of the QF1 converter with 30 ms and 5 ms steps (the later function has been shifted down by -2 A for clarity). The slope changes in the case of 30 ms generation are clearly visible.

more detail at the end of the 2006 SPS run.

In fact the problem was almost eliminated when the time interval between reference points of the nominal function was reduced down to 5 ms. The impressive improvement is illustrated for the QF1 circuit in Figure 6 where the residual error after *Autotrim* is compared for ramps with point spacing of 30 and 5 ms. The large error 'lobes' have disappeared for 5 ms spacing and the *Autotrim* procedure **converges with any point spacing**. The only exception is a residual swing that occurs at the point of transition between the cubic and the linear ramp near 1500 ms, see Figure 1. This may be cured by a smoother transition between the cubic and the linear ramp segment. The nominal ramp functions for the two cases are shown in Figure 5.

Given the important improvement for the regulation of the main converters, new ramps for FT beams will be generated in 2007 with 5 ms or 6 ms point spacing (to avoid integer multiples of the 20 ms 50 Hz period) for the start of the ramp, i.e. covering the first 500 ms of the ramp. For the standard LHC beam ramp such a reduction is not a priori necessary because of the much smoother and slower ramp start. It may however be valuable for the faster 4.2 s LHC ramp that is intended to be used to pilot beams.

3 Dipole Field Errors

A precise calibration of the SPS beam momentum at 450 GeV/c was performed in 2002 using the last Lead ion beam before the LHC startup [1]. The value of the beam momentum at the nominal setting of 450 GeV/c was found to be $P_{\rm ref} = 449.16 \pm 0.14$ GeV/c. The corresponding

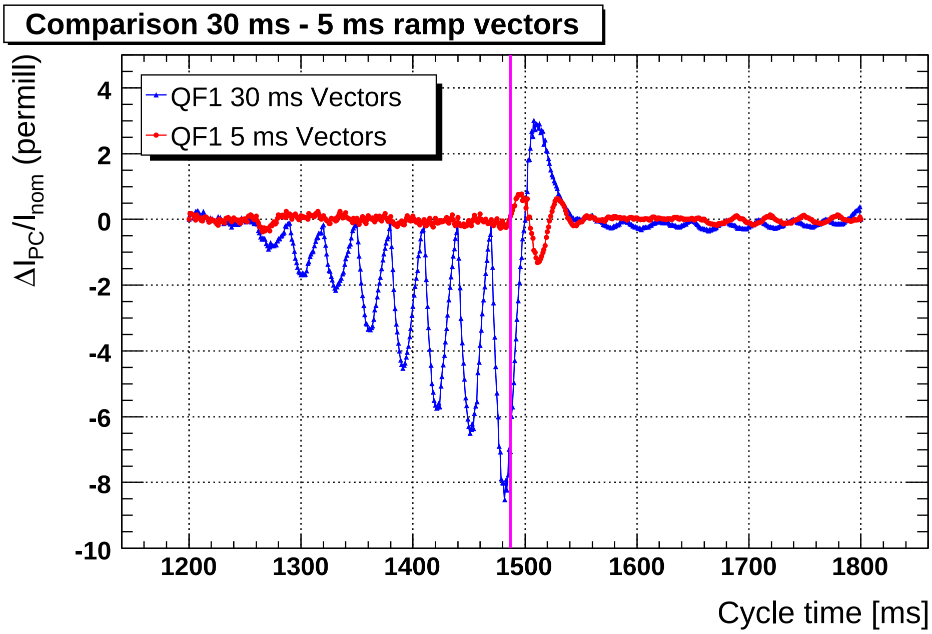

Figure 6: Residual current error of the QF1 circuit after applying the autotrim correction for a standard ramp generated with points separated by 30 ms and for a test ramp generated with points spaced by only 5 ms. In the later case the peak error is reduced by one order of magnitude and it occurs at the transition to the linea ramp at 1500 ms.

magnetic field determined with a NMR probe in the SPS reference magnet is $B_{\mathrm{ref}} = 2.0251 \pm 0.0002$ (T), see Table 1.

The NMR probes installed in the reference magnet in BA3 were used to estimate the beam momentum at various flat bottoms or flat tops (at least 1 second at constant field is necessary to lock the NMRs) [2]. The resulting calibrated momenta are given in Table 1. The same NMR probes were also used to determine the SPS field stability. At high energy the relative stability of the dipole field is better than 10^{-4}.

The calibration at 450 GeV/c was used for the commissioning of the TI8 transfer line in 2004. The TI8 main dipoles were set to a nominal momentum of 449.2 GeV/c and the beam did not show a significant momentum error in TI8.

For the CNGS commissioning in 2006, the transfer line momentum was initially set to 399.2 GeV/c which corresponds roughly to the same relative SPS energy error at 400 GeV/c than at 450 GeV/c. The first trajectory measurements indicated however a residual momentum error and the TT40 and TT41 transfer lines were finally set to 398.5 GeV/c, in good agreement with the NMR estimate for the SPS beam momentum given in Table 1.

The momentum settings of the TI8 and TT41 transfer lines also indicate that the calibration curves of the respective main dipole strings are accurate to the level of few times 10^{-4}.

The relative momentum error of the main dipoles with respect to the nominal setting can be determined with the SPS BTRAIN system [2]. A measurement of the field error is shown in Figure 7 for the nominal LHC beam ramp. The momentum error is obtained from a comparison of the magnetic field measured by the BTRAIN system and the nominal field. It is interesting to note the large swing of the energy error between 300 and 450 GeV/c which is correlated to systematic tune trims that are discussed in the section 5.

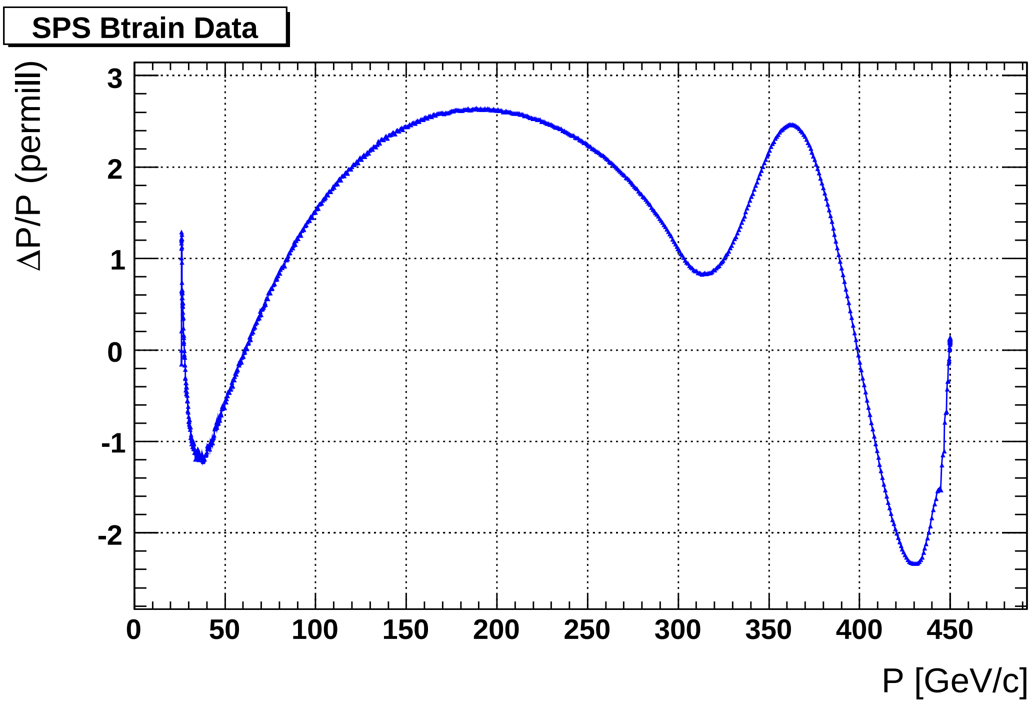

Figure 7: Relative momentum (dipole field) error for the nominal LHC beam ramp measured with the SPS BTRAIN system [2].

Reference P (GeV/c)	$\bar{B}$(T)	Measured P (GeV/c)
25.91	0.11669 $\pm$ 0.00002	25.88 $\pm$ 0.01
370.1	1.6650 $\pm$ 0.0003	369.28 $\pm$ 0.12
400.0	1.7954 $\pm$ 0.0003	398.22 $\pm$ 0.13
450.0	2.0251 $\pm$ 0.0003	449.16 $\pm$ 0.14

Table 1: NMR field measurements of the SPS reference magnet for a number of reference flat bottom or flat top momenta [2]. The nominal reference momentum is given in the first column. The second column gives the average dipole field $\bar{B}$ and the typical accuracy of the NMR measurement. The last column holds the estimated beam momentum obtained by extrapolation of the momentum calibration at 450 GeV/c [1] (for points below 450 GeV/c).

4 Eddy Current Effects at Injection

At injection long lasting eddy currents induce tune shifts and momentum variations that can induced coupling of the tune and dipole field settings of consecutive cycles if they follow at close distance in time. The tune and dipole field shifts depend on the time to the end of the main converter down-ramp from the preceding cycle, see Figure 8. The effect has been observed on a variety of cycles and studied systematically for the 3.5 GeV/c positron injection in 2000 [4]. A combination of different measurements is shown in Figure 9. The data includes results from 14 GeV proton injection for a CNGS cycle, from 26 GeV injection for an early LHC cycle (2002) and from 3.5 GeV positron injection [4]. The tune shifts have been corrected for the effect of the dipole field, i.e. they represent directly the quadrupolar field due to the eddy currents. Within the errors the tune shifts are identical for both planes. The data sets are very consistent.

The decays may be fitted by an exponential function for the tune

$$\Delta Q_{eddy} = \Delta Q_0 \exp(-t/\tau^Q_{eddy}) \quad (2)$$

and for the dipole field

$$\frac{\Delta B_{eddy}}{B} = \frac{\Delta B_0}{B_0} \exp(-t/\tau^B_{eddy}) \quad (3)$$

ΔQ_0 and $\Delta B_0/B_0$ are the initial amplitudes and τ_{eddy} are the decay time constants. A fit to the data yields

$$\Delta Q_0 = (0.14 \pm 0.02)\ \frac{14\ \mathrm{GeV/c}}{P} \quad (4)$$

and

$$\tau^Q_{eddy} = 470 \pm 40\ \mathrm{ms} \quad (5)$$

for the tune decay, where P is the beam momentum. A delay of typically 1.2 s (one CPS basic period) is required between the end of a down-ramp and the next injection to ensure that tune effects from eddy currents can be ”neglected” for protons at 14 or 26 GeV/c. This condition is not fulfilled for CNGS cycles as shown in Figure 9.

A fit to the relative dipole field decay yields

$$\frac{\Delta B_0}{B_0} = (1.4 \pm 0.2)\ \mathrm{permill}\ \frac{14\ \mathrm{GeV/c}}{P} \quad (6)$$

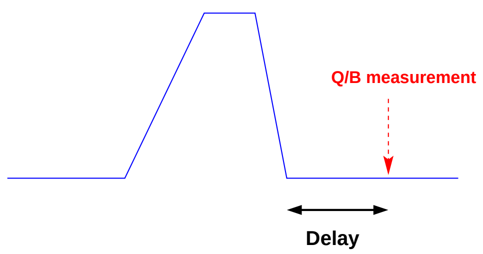

Figure 8: Definition of the time delay with respect to the end of a preceding down-ramp.

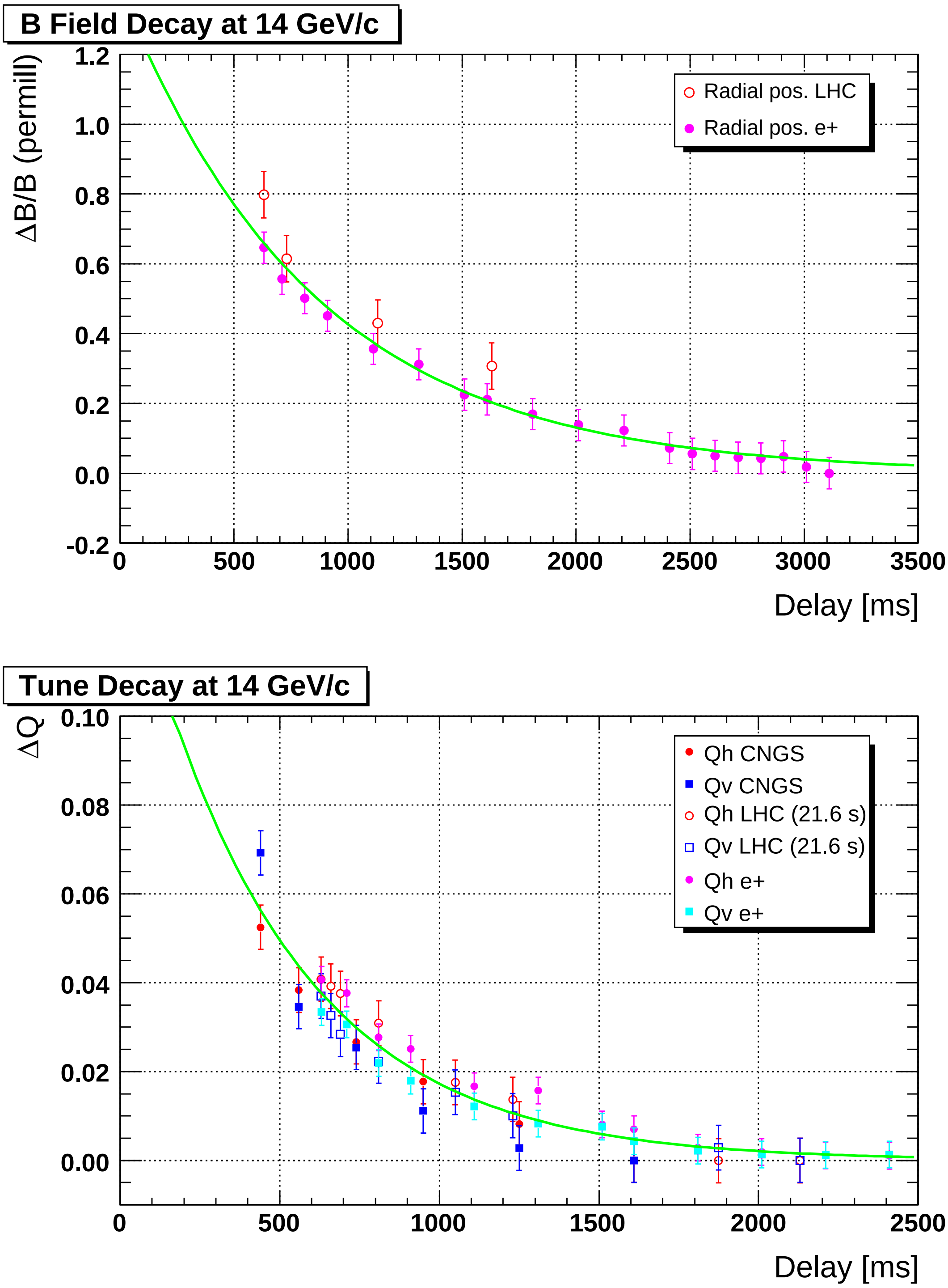

Figure 9: Dipole field change (top) and tune shift (bottom) induced by eddy currents from a preceeding down-ramp of the main converters as a function of the time delay to the end of the down-ramp. The main dipole field change was measured with the radial position of the first turn. The tune data is corrected for the tune shift induced by the dipole field. The data is normalized to 14 GeV/c. The solid green lines are fits to the data using Equations 2 and 3.

and

$$\tau^B_{eddy} = 850 \pm 60 \text{ ms} \tag{7}$$

The time constant for the decay is therefore twice as long for the main dipole field than for the quadrupole field. It is interesting to note that the ratio of time constants is consistent with the ratio of the magnet lengths. The tune shift induced by the dipole field error of Equation 3 is

$$\Delta Q_B = \frac{\Delta B_0}{B_0} Q'_{nat} = (-0.046 \pm 0.007) \; \frac{14 \text{ GeV/c}}{P} \tag{8}$$

where $Q'_{nat} = -33$ is the natural chromaticity of the SPS. The tune shift due to the (uncorrected) dipole field error represents therefore approximately 30% of the direct tune shift effect and has the opposite sign.

5 Tune Corrections in the Ramp

At the SPS the multiple tune measurement system (MultiQ) based on a chirp excitation of the beam provides a powerful tool for fast measurements of tune and chromaticity functions [3]. The technique works best for low intensity beams that can be run with low chromaticity and without transverse damper. The measurement and correction procedure is very efficient above transition. With this tools and thanks to the new LSA control system, the tune may be corrected over an entire cycle on the time scale of 15-30 minutes.

The tune corrections that had to be applied to reach the nominal tunes for FT beam (26.62, 26.58) and LHC beams (26.13, 26.18) have been collected and analyzed to better understand the machine reproducibility and to be able to anticipate tune corrections for new cycles in the future.

For the 2006 SPS run data from the following cycles have been analyzed:

- **FT** : the nominal FT cycle with a 1.26 second injection flat bottom and a momentum range of 13.9 to 400 GeV/c.
- **LHC** : the nominal LHC cycle with a 10.86 second injection flat bottom and a momentum range of 25.9 to 450 GeV/c.
- **LHCFAST** : a fast LHC cycle for pilot beams with a 60 ms injection flat bottom and a momentum range of 25.9 to 450 GeV/c.
- **FT25ns** : a special LHC cycle with a 60 ms flat bottom and standard LHC ramp from 25.9 to 400 GeV/c for a special bunched beam slow extraction ('25 ns run').
- **LHC270** : a coastable LHC cycle with an intermediate flat top at 270 GeV/c.

The tune corrections as a function of the beam momentum are shown in Figure 10 for the cycles mentioned above. Corrections for the LHC cycles exhibit a very small spread. Part of this spread is due to the fact that the reference tune may have varied by ± 0.005 from one cycle to another. Corrections for the FT beam follow the values of the LHC cycle between 50 GeV/c and 300 GeV/c. At 400 GeV/c the corrections are also consistent. The difference that is observed between FT and LHC beams between 300 and 400 GeV/c is due to a problem with the round-off of the FT ramp which resulted in the large additional corrections visible in Figure 10. Data from the former SPS control system indicates that there is no significant difference between FT

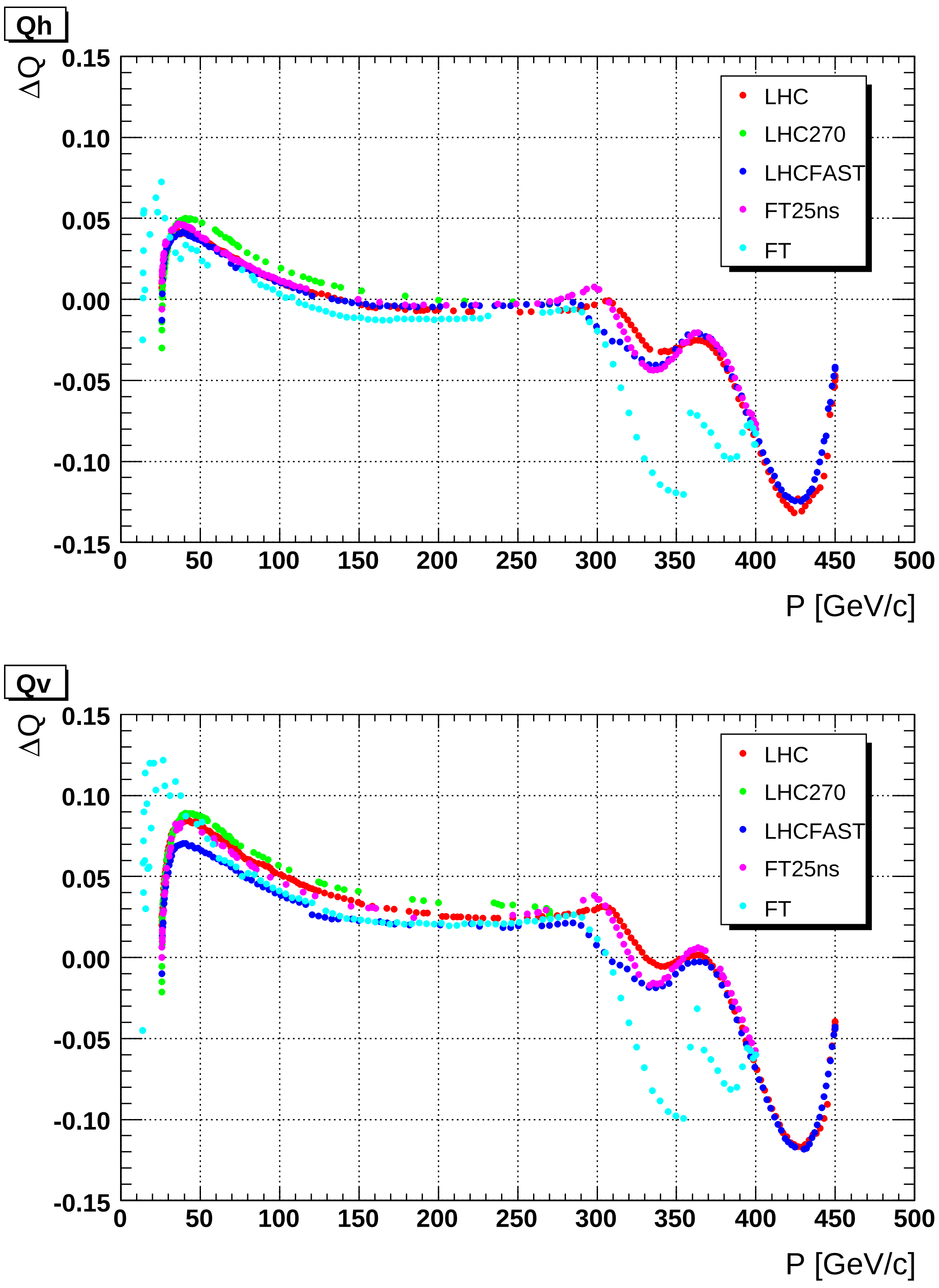

Figure 10: Tune trims for the horizontal (top) and vertical (bottom) plane for a variety of LHC cycles and for the FT cycle. The excellent reproducibility of the trims for the LHC cycle to 450 GeV/c.

and LHC cycles in that momentum range. The tune corrections are therefore consistent for all beams above 50 GeV/c. The corrections for the vertical and the horizontal plane are similar in amplitude and shape. The large swing of the correction between 300 and 450 GeV/c is perfectly correlated to the momentum error shown in Figure 7. Assuming a natural chromaticity of -33, the energy change of 0.25% between 400 and 450 GeV/c results in a tune error of $\Delta Q \approx +0.08$, in good agreement with the trims shown in Figure 10.

The tune correction averaged over all LHC type cycles is shown in Figure 11. The r.m.s. spread of the data is represented in the form of error bars. The FT beam have consistent correction in the range of 50 to 400 GeV/c.

The averaged data will be used in the future to anticipate the tune correction for new LHC beam cycles. The correction is expected to have an accuracy of the order of ± 0.01 which represents an excellent initial correction for the tune functions.

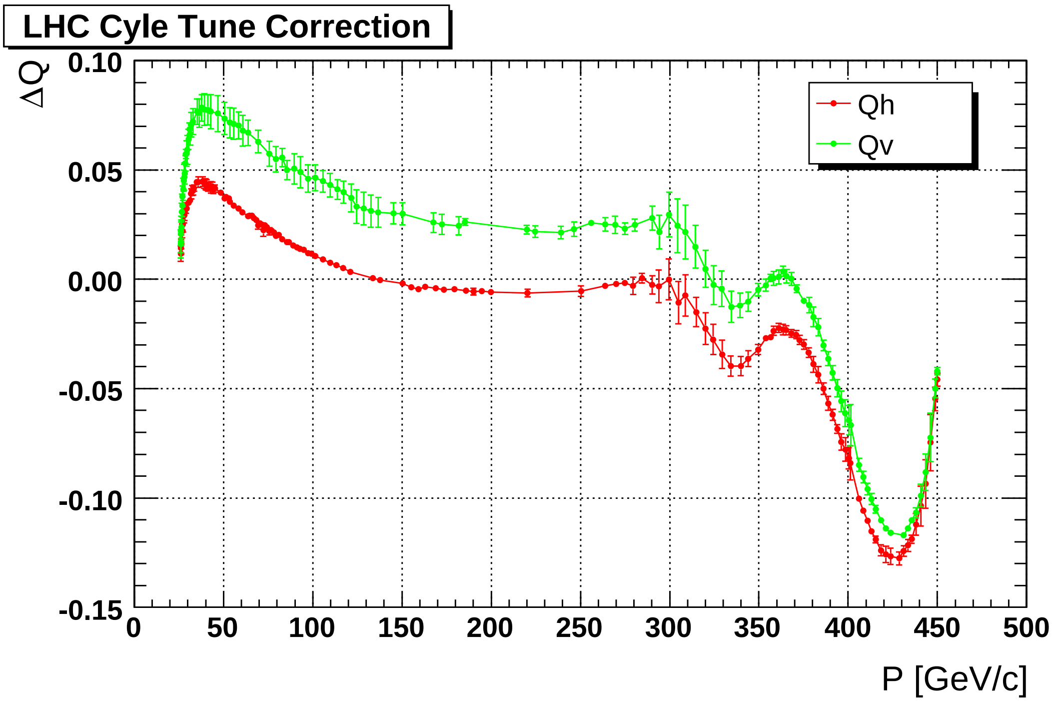

Figure 11: Average LHC cycle tune trims for the horizontal and vertical plane as a function of the beam momentum P.

6 Chromaticity Corrections in the Ramp

The standard SPS definition of the (normalized) chromaticity is

$$\xi_u = \frac{Q'_u}{Q_u} = \frac{\Delta Q_u}{Q_u \, \Delta P / P} \tag{9}$$

with Q_u the machine tune and P the beam momentum. The horizontal and vertical planes are labeled 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

$$\xi_u^Q = -1.257 \tag{10}$$

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

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). The total number of lattice quadrupoles is 216, i.e. there is only one sextupole for 2 quadrupoles.

Already in the design phase of the SPS, contributions to the chromaticity due to sextupolar field components from dipole magnets (remnant fields and saturation) and eddy currents on the vacuum chamber had been identified and evaluated [5]. The standard model used for those additional contributions (excluding the contribution due to ξ_u^Q) is based on 3 terms given by

$$\Delta\xi_u^{\mathrm{ind}} = a + \frac{b}{P} + c\,\frac{\dot{P}}{P} \tag{11}$$

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 remnant fields). The last component represents the effects of vacuum chamber eddy currents induced by the field changes during the ramp. The default parameter values used in the past years for machine settings generation, are given in the second column of Table 2.

An analysis of the chromaticity data for the LHC cycles led to the development of a new empirical model [3] that provides a better description of the data. The new model describes the chromaticity perturbations by

$$\Delta\xi_u^{\mathrm{ind}} = a + \frac{b}{P} + c\,\frac{\dot{P}}{P} + \left\{ \begin{array}{c} - \\ d\,(P-P_1)/(P_2-P_1) \\ d + e\,(P-P_2)/(450[\mathrm{GeV/c}]-P_2) \end{array} \right\} \left\{ \begin{array}{c} P \le P_1 \\ P_1 < P \le P_2 \\ P > P_2 \end{array} \right\} \tag{12}$$

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 to the data from super-cycles used in the 2002 run. The resulting parameter values 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 12. There is some indication that parameters a and b, that reflect the remnant field errors, depend on the the maximum field of the cycle (and in particular on the dipole saturation above 350 GeV/c). Lack of systematic data prevents however a more precise analysis. More details may be found in Ref. [3].

The chromaticity trims required to reach a chromaticity close to zero (i.e. in the range 0 to 0.1) are shown in Figure 12 together with the empirical model fits (Equation 12). Data from Ref. [3] determined in 2002 is compared to the recent trims obtained with the new LSA control system. The data sets are consistent within $\Delta\xi = \pm 0.1 - 0.2$.

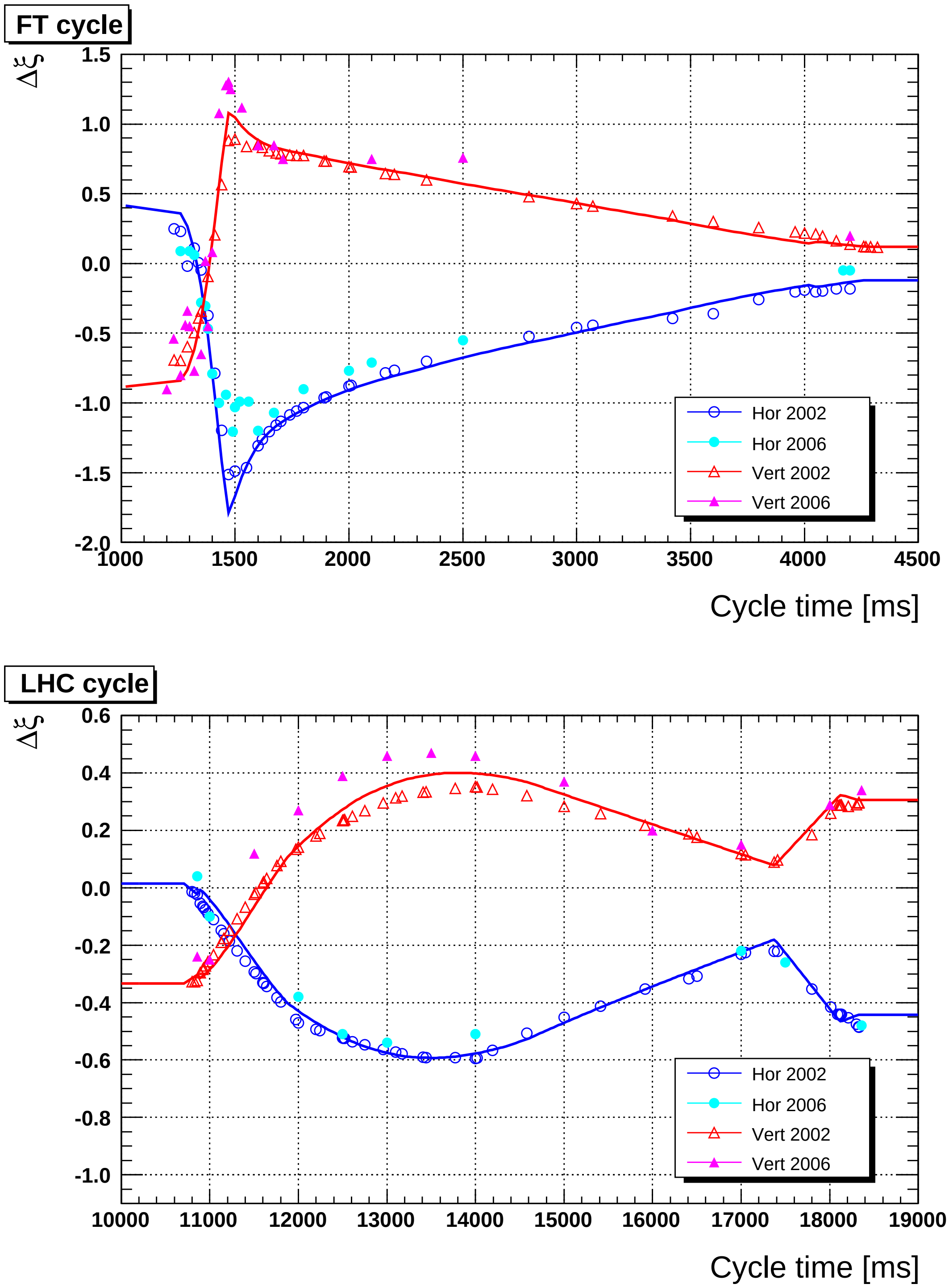

Figure 12: Chromaticity trims required to obtain a chromaticity near zero (< 0.1) for a standard FT (top) and a standard LHC cycle (bottom). The solid line is the fit to the model. In both cases, trim determined in 2002 [3] are compared to latest trims from the SPS run in 2006. In general there is agreement at the level of $|\Delta\xi| \leq 0.1 - 0.2$.

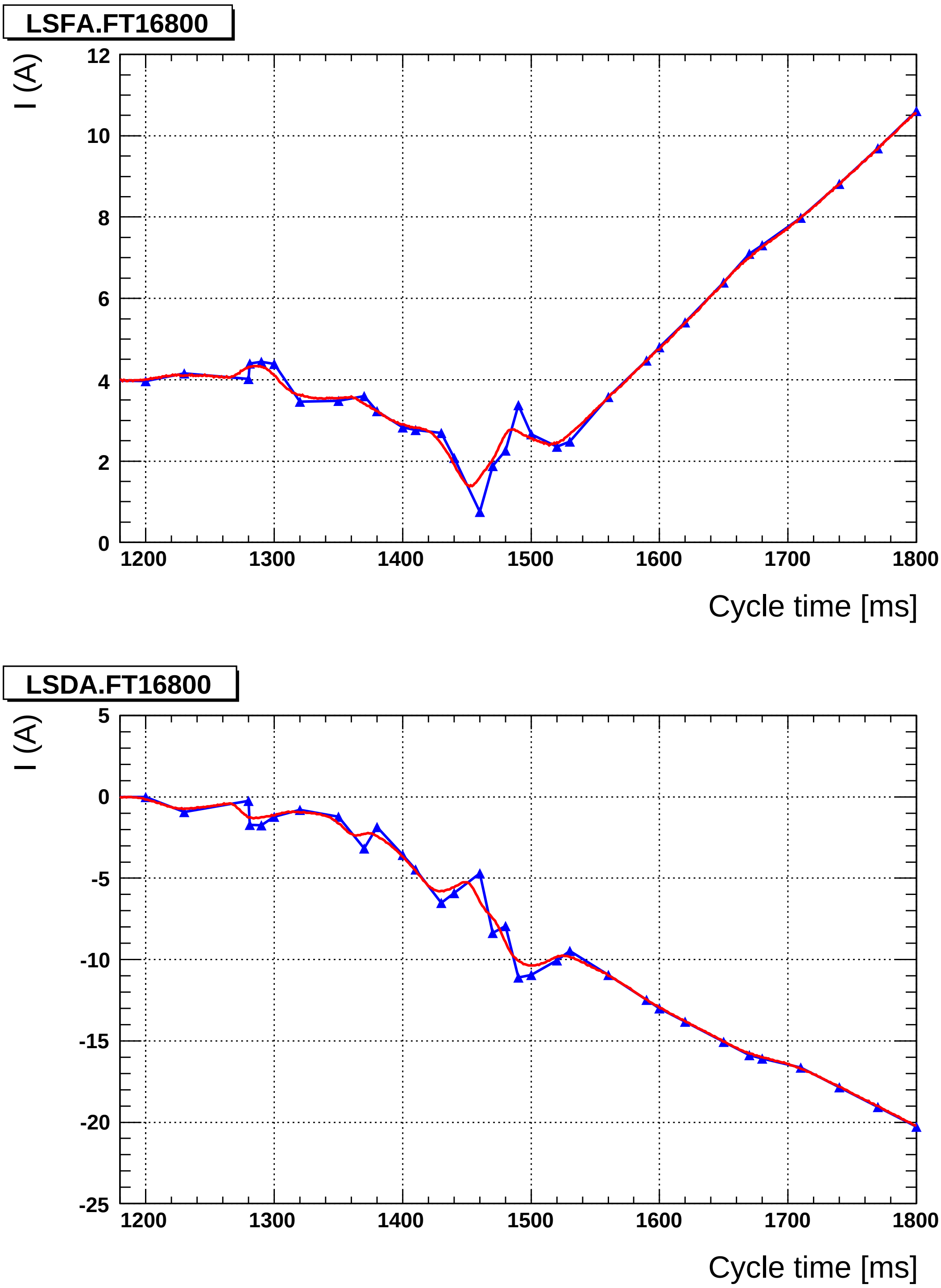

Figure 13: Comparison of the reference function (blue points) and the measured function (red line) at the start of the FT ramp for the LSFA and LSDA sextupole circuits.

Parameter	Horizontal Plane Model				
	Default	New / LHC		New / FT	
a	0.21	0.61	±0.02	0.54	±0.02
b (GeV/c)	-4.63	-16.2	±0.6	-13.3	±0.5
c (1/s)	0.30	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	New / LHC		New / FT	
a	-0.07	-0.52	±0.02	-0.55	±0.02
b (GeV/c)	10.0	22.0	±0.6	20.0	±0.5
c (1/s)	-0.28	-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 the second column. The fitted parameters for the new model (7 parameters) are given in the third column for the LHC beam cycle. The last column holds the parameters for the new model with parameters a and b readjusted to match the FT cycle.

6.1 Sextupole converter tracking

No autotrim correction is performed at the SPS for the lattice sextupole circuits. An example for the reference and measured current for the tuned FT cycle in 2006 is shown in Figure 13. It must be noted that the function send to the sextupole converters is advanced by 20 ms to take into account the regulation delays. One clearly notes that the power converter is not able to follow some of the current changes that are requested on a too short timescale due to the limited bandwidth. In fact some of the fast changes that were programmed in the chromaticity function in 2006 are probably neither needed nor desirable. The spikes are visible in Figure 12 on the data from the LSA control system. In the future such 'spikes' should be filtered by verifying the tracking of the converter.

The origin of the spikes is partly due to a new organization of the sextupole trims and settings. In the former control system the estimated corrections due to eddy currents and remnant fields were stored separately from the actual correction trim. As a consequence the steep changes due to eddy current for the FT ramp where hidden and the correction function was rather flat. In 2006 a unique function was used to store the entire chromaticity correction with its very steep slope in the early part of the ramp. Trims therefore tended to produce very 'spiky' structures. The chromaticity settings organization should be reviewed for 2007. In addition the tracking of the sextupole converters should be verified regularly, and structures of the settings that cannot be followed by the converters smoothed out.

7 Conclusion

The tracking errors of the main SPS power converters can be reduced by one order of magnitude by generating ramp points separated by 5 ms instead of the traditional 30 ms. This change will be implemented in 2007 for the start of the SPS main converter ramps. This should hopefully improve significantly the reproducibility of the cycles and ease the tune adjustments for the FT beams.

The calibration of the SPS momentum with Lead ions and with the reference magnet NMRs have been confirmed during the commissioning of the TI8 and CNGS transfer lines. At the nominal 450 GeV/c setting, the actual SPS momentum is 492.2 ± 0.2 GeV/c while at 400 GeV/c it is around 398.2 to 398.5 GeV/c.

Data from various cycles concerning the 'long' lasting eddy current at injection due to the down-ramp of the preceding cycle have been combined together. The data sets are very consistent and yield time constants of 500 ms for the tune decay and 900 ms for the dipole field decay.

Tune trims accumulated for the various cycles that have been used in 2006 were combined and yield a very consistent picture. The tune corrections are largely independent of the ramp speed and shape above 50 GeV/c. Between 50 and 450 GeV/c the tune trim at a given momentum seems to be (almost) identical for all cycles. A 'universal' tune correction can be deduced from the data that should be accurate to approximately ± 0.01.

The chromaticity corrections that have been re-tuned and remeasured 'from scratch' with the new control system agree with optimal trims from the SPS run in 2002 for the standard FT and LHC cycles.

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References

[1] G. Arduini *et al.*, *Energy calibration at the SPS with Proton and Lead Ions Beams*, AB-Note-2003-014 OP.

[2] J. Wenninger, *SPS Momentum Calibration and Stability in 2003*, AB-Note-2003-091 OP.

[3] J. Wenninger, *Dynamic Effects on Chromaticity for the LHC beam*, SL-Note-2002-041 OP.

[4] C. Arimatea and D. Jacquet, *Measures de l'influence magnetique du cycle proton 450 GeV sur le cycle positron*, SL-Note-2001-013-MD.

[5] Y. Baconnier *et al.*, *Correction elements and stopbands in the SPS*, LAB II-DI-PA/EJNW/pd, Nov. 1972, unpublished.