EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — SL DIVISION

CERN SL-99-047 BI

FIRST RESULTS ON CLOSED-LOOP TUNE CONTROL IN THE CERN-SPS

Jensen, L.; Jones, O.R.; Schmickler, H.
CERN – Geneva - CH

Abstract

This paper presents the first measurements performed with the SPS Qloop. The emphasis will be laid on the model used for designing the regulation loop and how well it fits reality.

Presented at DIPAC
Chester – 16-18 May 1999

Geneva, Switzerland
August, 1999

FIRST RESULTS ON CLOSED-LOOP TUNE CONTROL IN THE CERN-SPS

L. Jensen, O. R. Jones, H. Schmickler
CERN SL/BI, Geneva, Switzerland

Abstract

This paper presents the first measurements performed with the SPS Qloop. The emphasis will be laid on the model used for designing the regulation loop and how well it fits reality.

1. MOTIVATION

The SPS Qloop project was started as a follow-up to the 'LHC Dynamic Effects Working Group' workshop [1]. One of the results from this workshop was the expressed need for real-time feedback on the betatron tunes in the LHC, since the extensive use of super-conducting magnets mean that feed-forward tables will not suffice.

2. FEEDBACK PRINCIPLE

The use of feedback is well known in everyday life. An example is the use in air-conditioners. Designing a regulation loop involves knowledge of the time-constants and delays in the system one is trying to control. In the following paragraph we explain how a model was derived for the SPS Qloop.

3. MEASUREMENT OF QD TRANSFER FUNCTION

In the SPS Qloop, we use the main SPS quadrupole strings QD and QF for the correction of the betatron tunes. Measurements done by A. Beuret et al in 1995 showed that the transfer function of the power converter to the magnet has a –3 [dB] cut-off frequency of approx. 40 [Hz]. The measurement did not however take into account the possible time delay between the powering the magnets and their action on the beam. This delay is caused by the time it takes for the magnet flux to pass through the vacuum chamber and plays an important role for the limited bandwidth of the LEP Qloop. The measurement of the transfer function H(s) = Qv(s)/Iqd(s) was done during two SPS MD's, where sine-wave signals of varying amplitude and frequency were super-imposed on the quadrupole DC reference current. By doing harmonic analysis, the transfer function could be calculated [2]. In figures 1A and 1B, the resulting transfer function of the main SPS QD magnet string can be seen. A 2nd order Butterworth low-pass filter has been fitted to the results and a good agreement can be found up to the –3 [dB] frequency of around 28 [Hz].

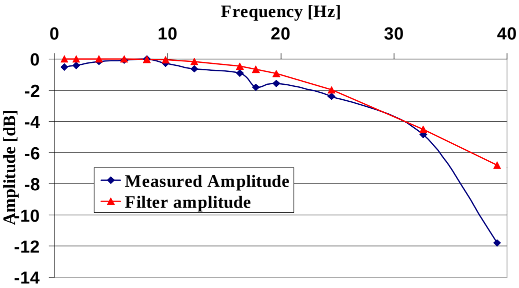

Figure 1A: Amplitude response for transfer function

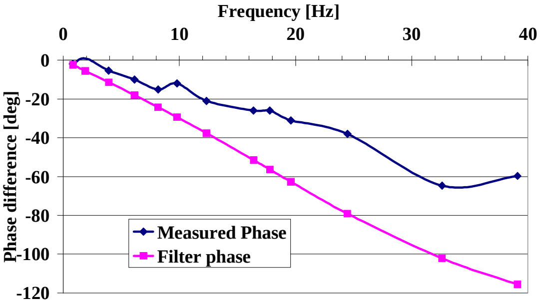

Figure 1B: Phase response for transfer function

4. MATLAB SIMULATIONS

From the above measurements, we learnt that we could approximate the transfer function by a 2nd order low-pass filter with a cut-off frequency of around 28 [Hz]. A widely used computer program called 'Matlab', with the 'Controls' toolbox and the 'Simulink' package, was used to design the regulation loop for the SPS Qloop. One of the most important parameters is the time between corrections, which in our specific case is given by the interval between individual tune measurements. Computation and transmission latencies for the corrections can be neglected in our case. For the tune measurements we are using 10 ms long chirp excitations and FFT transforms of the beam motion with automatic peak finding in the amplitude spectrum. In order to avoid possible problems due to coupling, only one plane is excited at a time. The tunes can therefore not be measured at an interval shorter than 20 ms.

The regulation loop should reduce the error as fast as possible without creating an excessive overshoot (thus requiring a certain phase and gain margin). Several books describe the design criteria for regulation loops (see e.g. [3]).

Figures 2 and 3 show the closed-loop response of the simulated system. The sampling frequency was chosen to be 50 [Hz]. The step response is shown in figure 2, while the error reduction as a function of frequency is shown in figure 3.

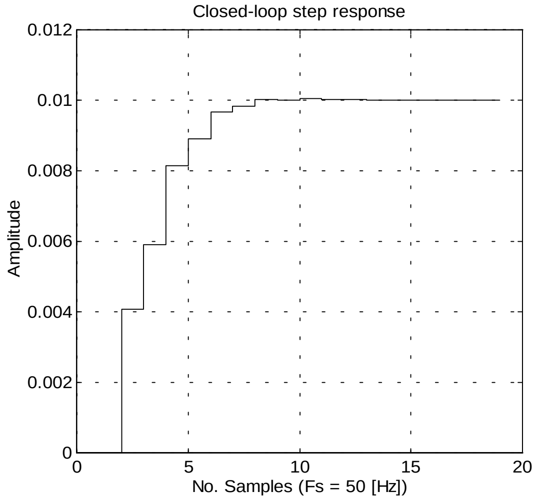

Figure 2: closed-loop step response

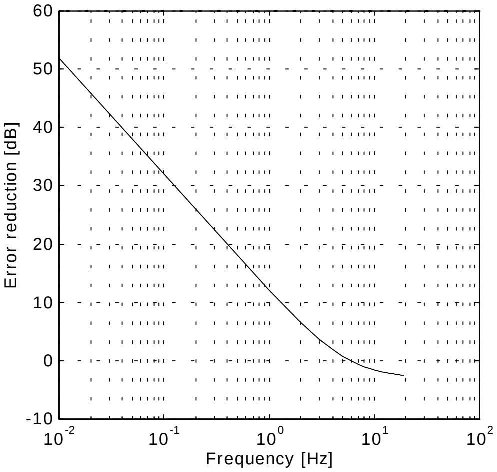

Figure 3: Closed-loop error reduction.

The zero dB roll-off point for the error reduction is found to be at around 5 [Hz], which is 1/10th of the sampling frequency. This is a general feature for sampled regulation loops. As the gain-bandwidth product is constant for a PI type regulation loop, tune excursions occurring at 0.5 Hz would be attenuated by the loop by 20 dB (a factor 10). This is a reasonable performance to correct the main tune excursions during the SPS acceleration period.

5. HARDWARE DESCRIPTION INCLUDING ATM

The SPS Qloop resides in a VME crate. The main CPU is a PowerPC running LynxOS. The real-time handling, which is done on a turn-by-turn basis, is performed using two DSP boards on the VME bus. A two-channel 16-bit input/output module is connected to each of the DSP boards and is used to sample the beam position and send the kicks used to excite the beam. An ATM PMC module is used to transmit the tune trim values to the power converters for QF and QD. This happens via an optical fibre of more than 1 [km] in length. In the power converter system, the trims are multiplied to the present current reference, thus making the knowledge of the present beam energy (quadrupole current) unnecessary. The ATM protocol, which was chosen as a communication prototype for LHC fast control, assures a known latency between sending a trim and receiving it at the other end. We are presently using a 120 Mbit/second connection with ATM AAL5 as interface level [4][5]. Measurements using a GPS module showed an average transfer time of the order of 200 [μsec]. This delay is short compared to the bandwidth of the system and plays no important role.

6. OPEN AND CLOSED-LOOP MEASUREMENTS

To check the performance of the SPS Qloop, several different tune distortions were programmed on the nominal quadrupole reference. We then measured the tune along the cycle with the feedback loop opened and closed. As can be seen from figure 4, the Qloop system managed to take out a triangular shaped distortion. An RMS error improvement of around 20 [dB] was calculated with respect to the nominal tune value of 0.64.

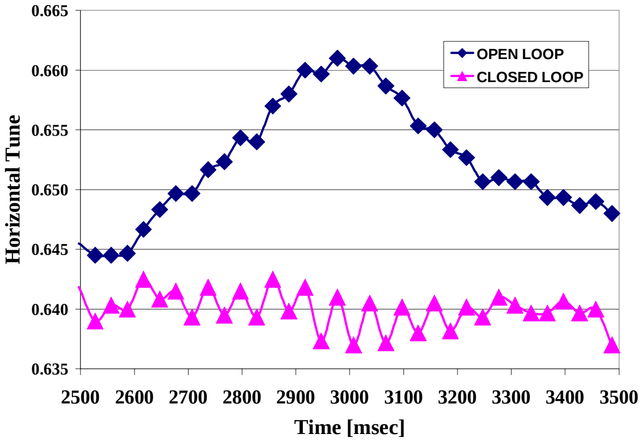

Figure 4: open and closed-loop response for a triangular tune distortion

7. THE FUTURE OF SPS QLOOP USING PLL TUNE MEASUREMENTS.

As discussed in chapter 4, (MATLAB simulations in figures 2 and 3) it will be difficult to achieve a tune regulation loop for the SPS with a gain-bandwidth product larger than 5 [Hz]. This limitation is due to the low bandwidth of the quadrupoles that are available to trim the tunes in the present configuration. Figure 5 shows the measured horizontal tune during the injection and ramp of the SPS. The larger excursions of the tune occur at transition energy. The two straight lines at the tune values 0.61 and 0.64 represent the boundaries, which seem acceptable for the acceleration of the LHC beams in the SPS. Most of the excursions at transition can be regulated out by the present SPS Qloop. Operational experience will show whether a higher bandwidth is required.

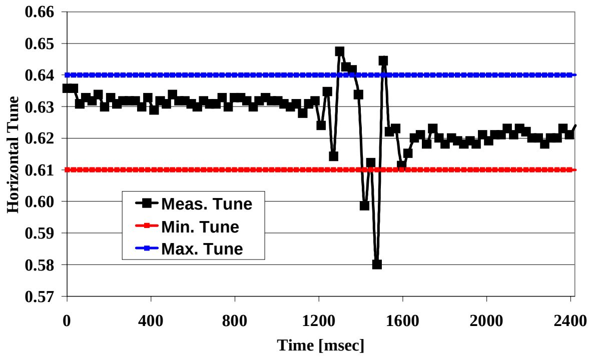

Figure 5: Measured horizontal tune during injection and acceleration

In case a higher bandwidth is required, additional faster quadrupoles will have to be installed in the machine. Such a project has already been studied for the so-called low-gamma transition lattice, which would require 24 additional quadrupoles [6]. If this becomes available, we would have to have to speed up the tune measurements in order to profit from the increased bandwidth of the quadrupoles. Such a faster tune measurement would be based on a Phase Locked Loop (PLL) [7], which could give tune readings at a rate of up to 500 [Hz] (i.e. 1% of the revolution frequency). Simulations, shown in figure 6 performed using the FastMap beam simulator [8] show that it is feasible to measure the tune using a PLL. The dotted line shows the reference tune value. The PLL is started with a tune value of 0.61, and after 400 turns the nominal tune of 0.62 has been reached. At 1000 turns, the reference tune is changed to 0.616, a change which the PLL tracks and locks on to after 200 turns.

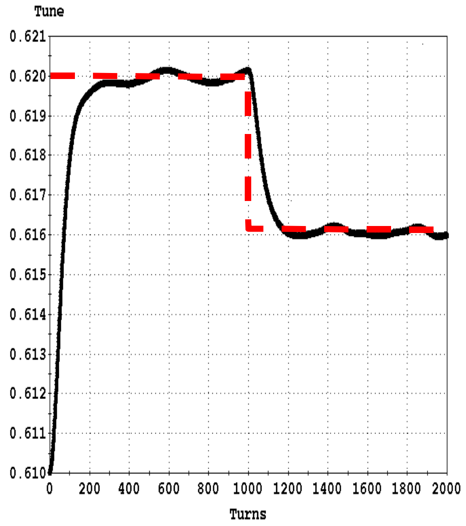

Figure 6: Simulation of lock-in and tracking process of PLL tune measurement

8. CONCLUSION

In this paper we have shown that the SPS Qloop in its present implementation (feedback on main quadrupole string, chirp tune measurements) can correct tune variations with a gain of 10 up to a bandwidth of 0.5 Hz. This speed is sufficient to correct slow tune distortions, which are typically encountered during the setting-up of a new cycle. In order to increase the bandwidth, additional quadrupoles with faster response times would have to be installed and in that case the tune measurements would be implemented using PLL techniques.

9. REFERENCES

[1]: 'LHC DEWG Workshop 1997 Summary'.

[2]: 'Measurement of the transfer function of the main SPS Quadrupoles' (SL-Note-98-047 MD).

[3]: 'Feedback control theory.' by Doyle, John C et al.

[4]: 'The Q-loop Project for the SPS' (SL-Note-98-014-DI).

[5]: 'Real Time Communications Prototyping for LHC Controls' (LHC-PROJECT-NOTE-174).

[6]: 'Additional quadrupoles, what can they be used for ?' (Proceedings of the 9th SPS-LEP performance workshop Chamonix, January 1999).

[7]: 'Phase-locked loops.' 3rd edition by Roland Best.

[8]: 'SPS and LHC Tune Control Studies using the "FastMap" tool (EPAC'98).