CHROMATICITY MEASUREMENTS VIA RF PHASE MODULATION AND CONTINUOUS TRACKING

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Abstract

Chromaticity diagnostics with high time resolution is of paramount importance for the control of the dynamic events in various accelerators, in particular for the LHC collider. This paper describes the possibility of measuring the machine chromaticity via RF phase modulation and continuous tune tracking. The RF phase modulation can be done at much higher frequencies than a classical RF frequency variation and thus, allows chromaticity measurements with a time resolution below the second. The paper describes the general measurement principle and discusses in detail open questions, which still have to be addressed experimentally. First results from machine measurements in the CERN SPS on beam stability during RF phase modulation are presented.

1 SEXTUPOLE COMPONENTS IN THE LHC DIPOLE MAGNETS

Persistent current decay changes the miltipole field components in superconducting magnets with time. These dynamic effects impose stringent control requirements for the operation of a superconducting storage ring. Table 1 shows a comparison of the maximum sextupole field error decay in existing and planned hadron colliders [1].

Table 1: *Expected chromaticity change due to the sextupole (b_3) persistent current decay in existing and planned super conducting hadron storage rings.*

machine	total b_3 generated Q'		$\Delta Q'$ due to b_3 decay	
	Q'_x	Q'_y	Q'_x	Q'_y
Tevatron	-140	+119	+8	-7
HERAp	-275	+245	+13	-11
RHIC	-38	+36	+2	-2
LHC	-450	+450	+150	-150

The change in chromaticity occurs over a time scale of ca. 20 minutes during the flat injection plateau and at the beginning of the ramp over a time scale of a few tens of seconds (depending on the initial ramp speed). Stable particle motion requires the control of the machine chromaticity within a window of

$$1 < Q' < 5. \qquad (1)$$

For negative chromaticity values the collective bunch motion becomes unstable and for chromaticity values larger than 5 units the single particle motion will become unstable. In order to control the chromaticity of the LHC within the window given in Equation (1) one needs to dynamically correct the b_3 field error of the dipole magnets within 0.5%. Such an accuracy is not achievable via reference magnet measurements [1] and requires additional beam based measurements.

1.1 Beam Based Chromaticity Measurements

The standard procedure for measuring the machine chromaticity is based on frequency modulations of the radio frequency (RF) system. Changing the RF frequency changes the beam energy and the central orbit in the machine. The energy and orbit variations change the machine tune proportionally to the total machine chromaticity. The above procedure tends to be slow (measurement rate lower than 0.1 Hz) and, due to the change in energy and orbit, perturbs the normal machine operation. Due to the limited momentum acceptance of the LHC this procedure is not compatible with the nominal LHC operation [2].

An alternative procedures for fast chromaticity measurements based on the head-tail oscillation of the bunches has been proposed in [3]. However, while the method satisfies the requirements on measurement precision and speed it turns out to blow up the beam emittance and can not be used during the nominal machine operation [4].

Controlling the machine chromaticity via beam based measurements in the LHC still requires the development of new measurement techniques which offer fast measurement rates with an accuracy of one unit in the chromaticity and which can be used during nominal machine operation without causing a deterioration of the beam parameters. In the following we discuss the possibility of measuring the chromaticity via RF phase modulation and continuous tune tracking.

2 CHROMATICITY MEASUREMENT VIA RF PHASE MODULATION

Similar to an RF frequency modulation, a modulation of the RF phase also changes the particle energy and orbit in the machine. However, compared to an RF frequency modulation the RF phase modulation can be done at much faster frequencies which lie outside the bunch spectrum (faster measurement procedure and no emittance blow up). Fig. 1 shows the resulting energy modulation versus the RF phase modulation frequency for a fixed modulation amplitude of 10 degrees. The solid line corresponds to a rigid bunch model and the dashed line to a soft bunch model. While the response of the rigid bunch always occurs at the excitation frequency, the response of the soft bunch always contains additional frequency components at multiples of the synchrotron frequency. For example, the two resonance responses in the soft bunch model at 157Hz and 380Hz both occur at the synchrotron frequency.

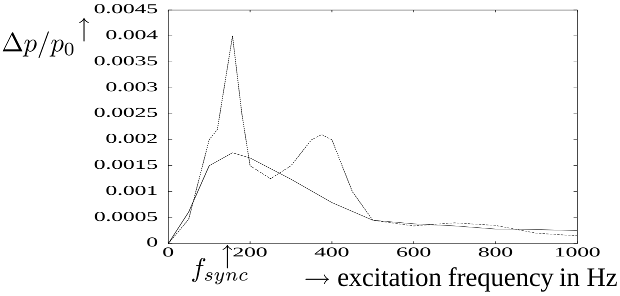

Figure 1: *Expected net energy modulation versus RF phase modulation frequency for a fixed modulation amplitude of 10 degrees for the SPS data. The solid line corresponds to a rigid bunch model and the dashed line to a soft bunch model.*

Two effects limit the choice of modulation frequency and amplitude. The RF phase modulation generates a net reduction of the RF bucket area and the maximum modulation amplitude will be limited by the available bucket area. A second constraint comes from the RF phase loop which will actively damp longitudinal oscillations. The modulation frequency must be chosen such that it does not interfere with the RF phase loop.

In the machine experiments performed in the CERN SPS we chose a modulation amplitude of 10 degrees and a modulation frequency of approximately five times the synchrotron frequency at which the RF phase loop is no longer active.

With the above limitations the RF phase modulation can generate only a small energy modulation ($\Delta p/p_0 \approx 10^{-4}$ for the SPS parameters) and we need to measure the resulting tune modulation via a high precision tune measurement. One possibility for measuring a tune modulation with an amplitudes of $\Delta p/p_0 \approx 10^{-4}$ is to frequency analyse the voltage signal of the voltage controlled oscillator (VCO) in a phase locked loop (PLL) circuit [5]. While this procedure allows a precise measurement of the modulation frequency it does not provide a measurement of the modulation amplitude and the measured signal requires calibration with an additional modulation signal of known amplitude. One possibility for such a calibration is to excite an additional tune modulation with slightly different frequency via a quadrupole circuit. The quadrupole modulation amplitude is increased until the two modulation amplitudes have the same amplitude in the Fourier spectrum and the tune modulation amplitude due to the RF phase modulation must be equal to the (known) amplitude of the quadrupole modulation. Since the energy modulation is known, the absolute value of the machine chromaticity can then be deduced via

$$|\Delta Q| = |Q\prime| \cdot |\frac{\Delta p}{p_0}|, \tag{2}$$

where $Q\prime$ is the machine chromaticity. Another possibility for calibrating the Fourier spectrum is to choose the quadrupole modulation frequency equal to the RF phase modulation frequency and with a constant phase relationship of 180 degrees between the two signals. If the tune modulation amplitudes of the two excitations is equal the corresponding frequency will not appear in the Fourier spectrum. While the first calibration technique generates a net tune modulation that might deteriorate the long term stability of the particle motion the second technique will not impose a net tune modulation to the particle motion. A second advantage of the second technique is that, in addition to the absolute value of the machine chromaticity, it also provides the sign of the chromaticity.

Fig. 2 shows a schematic layout of the required measurement setup.

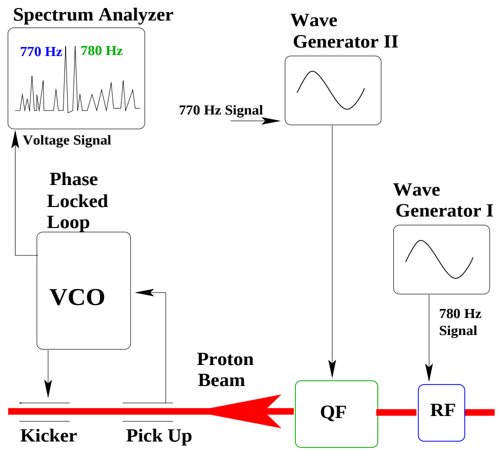

Figure 2: *Schematic setup for a chromaticity measurement using a PLL.*

3 MEASUREMENT SETUP IN THE CERN SPS

First measurements in the CERN SPS had the goal of demonstrating that an RF phase modulation with an amplitude of 10 degrees and a frequency of 600Hz to 800Hz does neither cause particle losses nor emittance growth. Because there was no PLL available in the CERN SPS at the time of the measurements we could not yet demonstrate the full functionality of the above measurement procedure. However, by measuring the Fourier spectrum of a transverse orbit pickup at a dispersion free location the measurements could demonstrate that the RF phase modulation indeed generates a signal in the transverse plane which is proportional to the machine chromaticity. The measured beam response to a transverse excitation depends on how close the excitation frequency is to the betatron oscillation frequency. In the presence of tune modulation (periodic change of the betatron frequency) an excitation at fixed frequency will thus generate a pickup signal that is modulated at the tune modulation frequency. In order to avoid spurious signals through dispersion at the pickup location we used an excitation in the vertical plane and a vertical pickup in the SPS experiments.

4 FIRST MEASUREMENT RESULTS

Table 2 shows the main machine parameters and Table 3 the main parameters for the measurements in the CERN SPS.

synch freq	RF frequency	energy (inj)	# of bunches	particles / bunch
157Hz	200MHz	26GeV	1	$4 \cdot 10^{10}$

Table 2: *Main machine parameters for the measurements in the CERN SPS.*

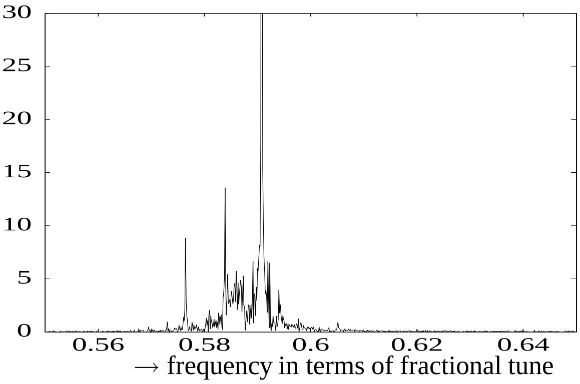

Figure 3: *Non-normalised spectrum of the beam position monitor reading for a vertical excitation at 17.74kHz and an RF phase modulation of* 10° *at 615 Hz. The vertical axis shows the frequency in terms of the fractional tune (i.q.* f_{line}/f_{rev} *and* $1 - f_{line}/f_{rev}$*) and the horizontal axis the amplitude of the spectral lines in arbitrary units on a linear scale. The spectral line at the left corresponds to the RF phase modulation frequency and the spectral line at the right to the vertical excitation frequency. The spectrum was taken for a machine chromaticity of 10 units.*

modulation frequency	modulation amplitude	transverse excitation	betatron tune
615Hz (0.5764)	10°	17.74kHz (0.5904)	25.569kHz (0.5905)

Table 3: *Measurement parameters for the CERN SPS. The upper value for the transverse and longitudinal excitation and betatron frequencies show the frequencies in Hz and the lower values give the corresponding fractional tune values.*

All measurements in the CERN SPS were done on a single bunch at injection energy (26GeV) with an RF phase modulation amplitude of 10 degrees in the 200MHz travelling wave RF system. The modulation frequency was varied between 600Hz and 800Hz

Fig. 3 shows a typical spectrum of the beam position monitor reading. The vertical axis shows the frequency in terms of the fractional tune (i.q. f_{line}/f_{rev} and $1 - f_{line}/f_{rev}$). One clearly recognises the frequency line of the RF phase modulation on the left side of the spectrum at $Q_{RF} = 0.576$ (615 HZ) and the vertical excitation frequency at $Q_{excitation} = 0.59$ (17.74 kHz) on the right. Fig. 4 shows the amplitude of the spectral line corresponding to the RF phase modulation as a function of the machine chromaticity. One clearly recognises that the measured spectral line increases with the machine chromaticity.

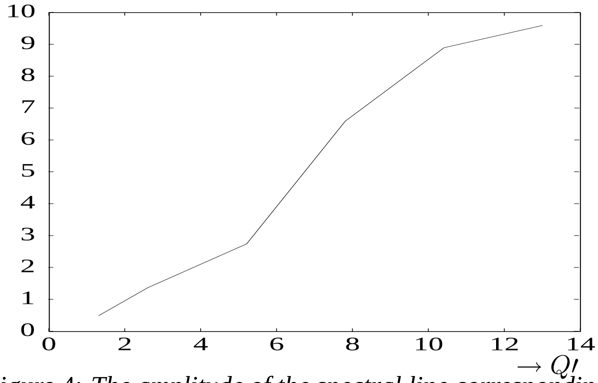

Figure 4: *The amplitude of the spectral line corresponding to the RF phase modulation as a function of the machine chromaticity.*

5 SUMMARY AND FUTURE PLANS

The first measurements in the CERN SPS showed that an RF phase modulation can be used to generate an energy modulation of $\Delta p/p_0 = 10^{-4}$ at 600Hz to 800Hz without generating particle losses or longitudinal emittance growth. The measurements further showed that the resulting transverse tune modulation is proportional to the machine chromaticity. The next steps for validating the proposed method for a fast chromaticity measurement include a continuous tune measurement with a PLL and a calibration of the PLL spectral lines via an additional tune modulation using quadrupole circuits.

6 REFERENCES

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