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Diagnostics and Control of the Time Evolution of Beam Parameters

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Abstract

Measurement tools for the betatron tunes, chromaticity and coupling exists in every circular accelerator. This article reviews diagnostic tools for the time evolution of these beam parameters in view of potential online feedbacks on magnetic elements in the LHC. For chromaticity measurements a new development made at CERN based on the detection of the phase difference between head and tail betatron oscillations is presented.

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Diagnostics and Control of the Time Evolution of Beam Parameters

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Abstract: Measurement tools for the betatron tunes, chromaticity and coupling exists in every circular accelerator. This article reviews diagnostic tools for the time evolution of these beam parameters in view of potential online feedbacks on magnetic elements in the LHC. For chromaticity measurements a new development made at CERN based on the detection of the phase difference between head and tail betatron oscillations is presented.

Introduction: The following work has been stimulated by the participation in a working group called "*Dynamic Effects Working Group*" at CERN. In this working group various aspects of time varying magnetic fields and their control are studied for the LHC [1]. In particular at the beginning of the acceleration large variations of the betatron tunes, the chromaticities and coupling over a few seconds can be anticipated.

The author has collected experience from FNAL (Tevatron) , DESY (HERA-P), from older proton machines at CERN (SPS, ISR, PS) and from LEP on the subjects of measurement tools and eventual online feedback loops.

1. TUNE MEASUREMENTS

1.1 Fourier Transform (FFT) of beam motion:

The most common method for tune measurements is the excitation of a beam motion (in most cases broad band excitation with white noise) and the computation of the power density spectrum in frequency domain. The betatron tunes are determined as the frequency with the highest amplitude peak. The frequency resolution Δf is inversely proportional to the number of oscillation samples (Nsamp). One can write: $\Delta f = 2/\text{Nsamp}$. So if for example one needs a tune resolution of 10^{-3}, at least 2000 samples have to be acquired. A modern computer can perform the time frequency transform (FFT) of 2048 samples in about 1 msec. For typical signal to noise ratios about a factor 4 can be gained in tune resolution by interpolation between the measured amplitude values [2]. If there is enough external excitation from other sources (ground motion, power supply ripple) or the beam is slightly unstable by itself the method also gives useful information without specific beam excitation. The signal to noise ratio can be improved by averaging several spectra into one measurement display.

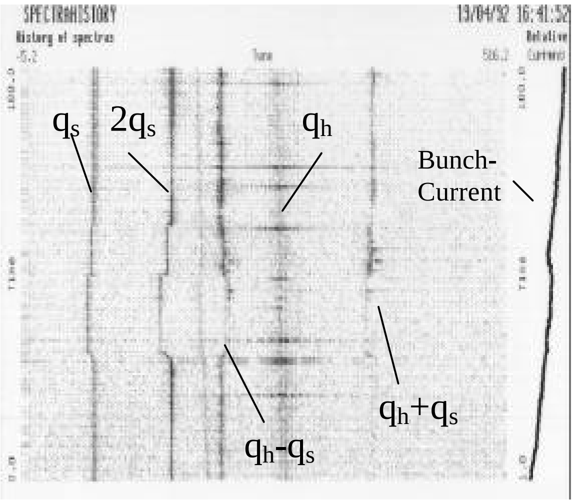

Fig.1: Accumulated spectra during LEP injection.

The time evolution of the tunes can be measured by accumulating many spectra and presenting them in a mountain range display. Figure 1 gives an example measured in LEP during injection. This figure nicely illustrates the diagnostic power of accumulated spectra. Apart from the horizontal tune multiples of the synchrotron tune and the synchrotron sidebands of the horizontal tune are visible. During a certain period two Rf-cavities had tripped (visible as shift in the synchrotron tunes). Such a tool is indispensable for machine set up and the study of many dynamic processes.

1.2 Chirp Excitation

As a variant of the previous method the beams are excited with a sine wave of time variable frequency. If one sends the excitation signal to a loudspeaker one gets the impression of a singing bird (at least at large machines!). For this reason the excitation is called "chirp" excitation. The chirp range is set around the expected betatron tunes and the length is taken corresponding to the requested time resolution and precision of the tune measurements. Data analysis of the resulting beam motion is either via sliding window Fourier transform or via a wavelet analysis [3]. The advantage of this method compared to noise excitation is that the phase information between excitation and beam motion is easier obtained and hence due to the better signal to noise ratio smaller excitation amplitudes can be used. Figure 2 shows the result of a chirp measurement in the SPS. The sweep length is 20 msec and the repetition rate is 30 msec. In total 150 chirp measurements cover acceleration. More details can be found in [4].

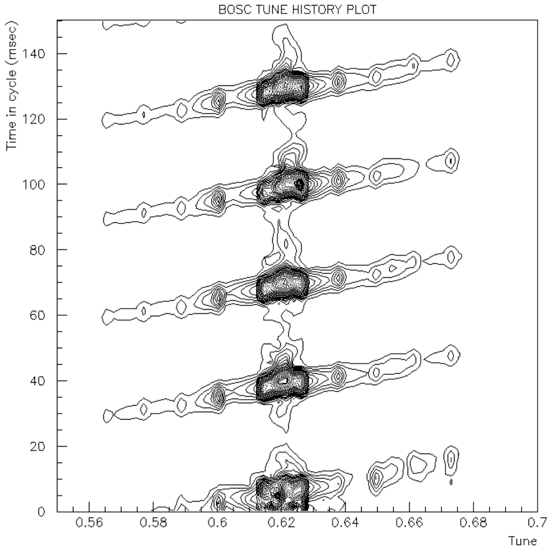

Fig. 2: Chirp tune measurement in the SPS. The horizontal scale is tune, the vertical scale is time (msec). The amplitude of the beam motion is encoded as grey scale.

1.3 Swept Frequency Analysis

For this method (often called “Network Analysis”) the beams are excited with a steady sinusoidal wave. Amplitude and Phase of the resulting oscillation are precisely determined by means of harmonic analysis. Thereafter the excitation frequency is increased in steps until the range of interest is covered. This represents a very precise measurement yielding the full information of the beam transfer function. The disadvantage is the long measurement time, which renders the method of little use for the study of dynamic phenomena. Details can be found in [5].

1.4 Phase Locked Loop Tune Tracker (PLL)

Most tune measurements use the amplitude peak of the beam oscillation as signal for tune measurements. This is somewhat odd, since the amplitude information with “0-slope” at its maximum suffers much more from noise than the phase information, which has its maximum slope at the tune resonance. Phase Locked Loop Circuits instead make use of the phase slope. The beams are excited with a continuos sine wave. By changing the frequency of the exciting oscillator an analog or digital circuit assures that the phase difference between excitation and beam motion is 90^0. The tune measurement simply consists in a readout of the (filtered) frequency of the oscillator. In reality the design of such a PLL is more complicated, in particular the lock-in procedure and additional regulation circuits for constant amplitude of the beam oscillation. Many details can be found in [6]. As the readout of the oscillator frequency can be made almost continuos a PLL circuit is the ideal tool for tracking the time evolution of the betatron tunes during machine transitions. Good measurement examples can be found in chapter 2.1 and 3.1 of this report.

1.5 Discussion

Common to all tune measurements is an exciter and an oscillation detector. The most natural approach is to implement the data treatment and the synthesis of the beam stimulus as a digital process of a system located “between” the monitor and the exciter. With the computing power of modern digital signal processors this should be a possible concept even for machines with revolution periods down to the microsecond. In that case the change in functionality is realised by a software reload.

The following functionalities are imported for the study of dynamic machine processes:

- Accumulated FFT spectra. Apart from the betatron tune lines other important spectral information is contained in the measurements. Beam excitation is done with random kicks or chirp signals.
- PLL tune tracking. In contrast to the previous method only the values of the betatron tunes are measured. With a good compromise in time resolution versus measurement noise a new tune reading is obtained every 100 machine turns.

The **Emittance Blowup** due to the beam excitation is of little importance for lepton machines, but this aspect is the key question for a proton machine. For machine studies and measurements during the setting up emittance blowup to a certain level can be tolerated, but on the operational beams for luminosity production one will only occasionally use a measurement with large (mm) oscillations. Accumulated or integrated spectra are very useful as they can be done without any excitation. In case the beams are quiet or kept quiet with a transverse feedback the use of chirp excitations can be considered, as the beam stimulus is centred around the region of interest. PLL tune tracking is on the first sight the worst one can do, as the beams are continuously excited on the resonance. On the other hand the very good signal to noise ratio of a PLL allows to work with sub micron beam oscillation amplitudes. Although not yet completely operational it has been shown at HERA-P that an online PLL tune measurement on two of the bunches of an operational beam was used for long periods without significant blowup [7].

2. Chromaticity Measurements

2.1 Variation of beam momentum

The commonly used method works by measuring directly the quantities involved in the definition of the chromaticity ξ. The definition is:

$$\Delta q = \xi \cdot \frac{\Delta p}{p} = \xi \cdot \alpha \cdot \frac{\Delta f_{RF}}{f_{RF}} \tag{1}$$

(α = momentum compaction factor)
i.e. one measures the tune dependence Δq on beam momentum ($\Delta p/p$), which is very often done by varying the Rf-frequency ($\Delta f_{RF}/f_{RF}$).

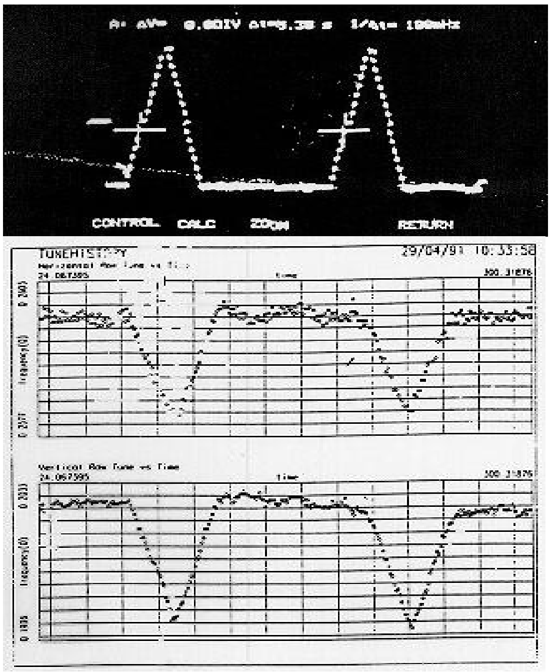

Fig. 3 Dynamic Chromaticty Measurement in LEP. Rf-frequency modulation measured on the tuning system (top trace) and tunes measured in PLL mode (bottom traces).

Figure 3 illustrates the measurement procedure implemented for LEP [8]. The tunes are measured in PLL mode (bottom traces) and the Rf-frequency is modulated in a three second long cycle with an asymmetric wave shape. The asymmetrie of the modulation is important, as it allows to identify the sign of the chromaticities from the tune measurements. This is nicely visible in figure 4, which shows a chromaticty meaurement during a beta squeeze of LEP. The top trace shows a diminishing horizontal chromaticity, which changes sign and then returns back to nominal sign and magnitude. The vertical chromaticity stays almost constant.

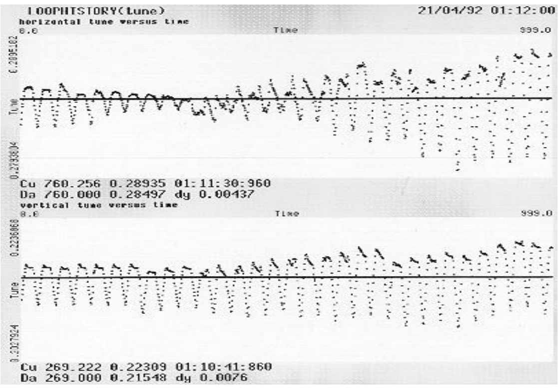

Fig.4: Horizontal (top trace) and vertical (bottom trace) chromaticity measurements during the beta squeeze in LEP.

2.2 Amplitude of Synchrotron Sidebands

The amplitude ratio of the betatron lines to their synchrotron side bands contains information on the chromaticty of the machine. This could well be used on accumulated tune spectra during machine transitions in order to get chromaticity information, but if the betatron tunes change a lot, it is not clear whether systematic lattice resonances influence the observed amplitude ratio. Studies have been made in LEP [9], but the issue has not been continued. In particular in proton machines the measurements are quite difficult, as the synchrotron tune is low and the signals of the side bands are often swamped in the spectral leakage of the main line.

2.3 Width of Tune Resonance

Using again equation (1) one can see that the momentum spread of the beam will result in a width of the betatron lines. Hence measuring the width of the resonance (best via swept frequency analysis (see chapter 1.3)) could be used as a measure of chromaticty. But there are other effects contributing to the line width (radiation damping, transverse feedbacks...), such that one normally looks only for variations in the width in order to deduce chromaticity changes. But in particular during acceleration this analysis is quite complicated, as the momentum spread changes during the measurement.

2.4 Frequency Shift in Bunch Spectrum

The longitudinal bunch profile generates a certain frequency spectrum in an electromagnetic coupler. If one excites betatron oscillations the longitudinal shape of the bunch changes depending on the chromaticty and hence will result in a different bunch spectrum. A detailed analysis yields that in frequency domain the measurable quantity is a shift in the peak of the bunch spectrum [10]. Experiments with this method are quite difficult and are at present not exploited for routine operation.

2.5 Phase of Head and Tail Betatron oscillations

This method is presently under development at CERN and has been stimulated by the ideas of the previous method. Rather than measuring in frequency domain the shift in bunch spectrum, the betatron oscillations of head and tail are individually sampled in time domain. The observable linked to the chromaticty is the phase difference between the head and tail oscillations. By the exciting kick this phase difference is initially forced to zero, evolving to a maximum after half a synchrotron period and then the oscillations rephase again after one complete synchrotron period. Figure 5 shows a computer simulation of the head tail motion for non zero chromaticty for illustration. The vertical axis is time (in [ns] along the longitudinal bunch profile), the horizontal axis is the revolution number after the kick stimulus and the amplitude of the betatron oscillation is encoded as grey scale. The head and tail oscillations are sampled in time slices indicated by the horizontal lines.

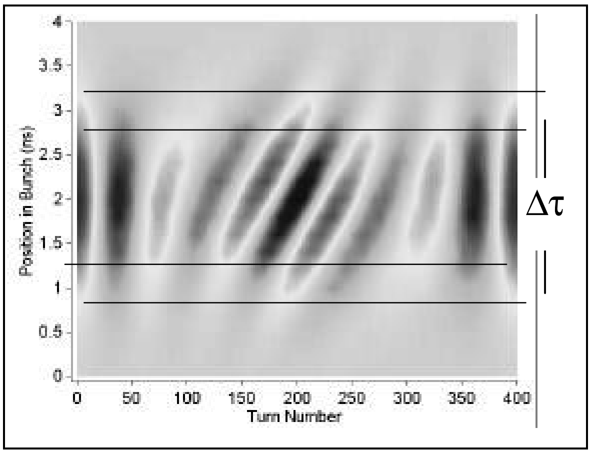

Fig. 5: Computer simulation of head-tail motion.

The chromaticity can be expressed as follows:

$$\xi = \frac{-\eta \cdot \Delta\Psi_i}{Q_0\omega_0\Delta\tau\left(\cos(2\pi \cdot iQ_s)-1\right)} \qquad (2)$$

with: $\eta=1/\gamma 2-\alpha$; Qs = synchrotron tune, ω_0 = angular revolution frequency; $\Delta\Psi_i$ = head-tail phase difference, $\Delta\tau$ = sampling time interval (see figure 6),
Q_0 = betatron tune and i turn index since initial kick

Practically the measured chromaticity does not depend on the betatron tune, as Q_0 in equation 2 is the total tune of the machine. A first series of measurements have been performed in the SPS in order to validate the basic idea. The results are very good. For instance an agreement within 15% of the chromaticty measured via momentum change and the new method could be found over a wide range of chromaticities. One dataset from these measurements is reported in figure 7. It shows the measured head-tail phase shift turn by turn for 3 different values of of the sampling time interval Δτ. As expected from equation 2 the dependence is linear. Any explanation of experimental details would leave the scope of this paper, but can be found in [11]

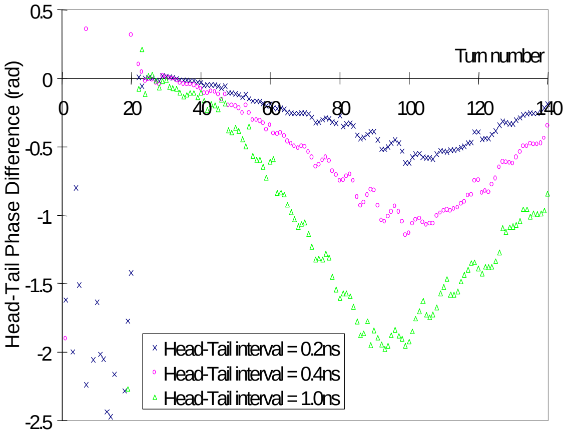

Fig. 6: Measured phase difference of head-tail betatron oscillations for 3 different sampling time intervals.

2.6 Discussion

By variation of the beam momentum and tune tracking a solid operational tool is available for dynamic chromaticity measurements. By extending the range of momentum variation even the non linear part of the chromaticty curve can be examined. But still the method has some limitations: The rate by which the beam momentum is changed can not made extremely short, for example in LEP the modulation cycle is limited to a 3 second interval. This is certainly too long for a chromaticity measurement during the start of acceleration, were a time resolution as short as 100 msec would be of interest. The LHC will require for the nominal beam currents tight control of the orbit, in particular in the collimation region. Periodic momentum changes and hence orbit changes in dispersive regions will be a problem. Secondly if one imagines the use of an online tune regulation loop a chromaticty measurement based on tune differences is very unfavourable. In that case the chromaticty would have to be deduced from the trims that the regulator has send to the quadrupoles in order to keep the tunes constant. With some sense for practical implementations one feels that this would not work!

For these reasons the development work on the head-tail sampling has been launched. The method provides a chromaticty reading independent of the betatron tunes and a measurement time of one synchrotron period (15 to 50 msec in case of the LHC). Further analysis will show the influence of octupolar fields, the limit in signal to noise ratio and consequently the amount of emittance growth that is linked with a single measurement.

3. Coupling Measurements

Coupling Measurements and Control are also important for the LHC. As the working point will be very close to the diagonal a bad compensation of betatron coupling will make tune and chromaticty measurements almost impossible. A very good and comprehensive summary of linear betatron coupling can be found in [12].

3.1 Closest Tune Approach

For this method both betatron tunes are measured during a linear power converter ramp, which crosses the values of the horizontal and vertical tunes. The remaining separation of the tune traces is a direct measure for the total coupling coefficent $|c|$. A measurement example from is shown in figure 7. In order to ensure that the PLL keeps tracking both tunes even when they approach each other the measurements are done on two different bunches.

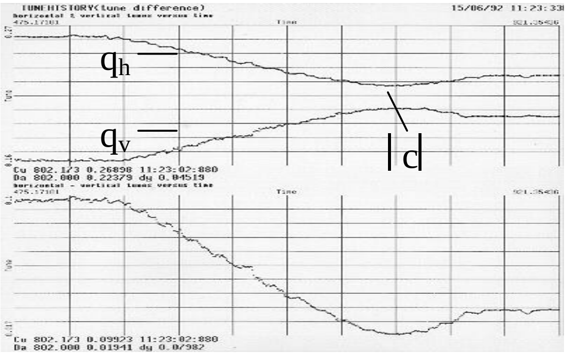

Fig. 7: PLL tune tracking during a swap of the tunes. The two top traces show the tunes, the bottom trace the tune difference reading.

3.2 Kick Method

The above method does not allow diagnostic during machine transitions. A better tool, although demanding quite large beam excitations for the measurement of small coupling coefficients, consists in applying a single kick in one plane and observing the time evolution of the betatron oscillations in both planes. The method is described in [12].

Summary

Comprehensive tools for tune, chromaticty and coupling measurements will be available for the diagnostic of dynamic phenomena in the LHC. The major development effort over the next years will be to improve the signal to noise ratio of the oscillation detectors for minimising the emittance blowup during the measurement. Control of the time evolution of these beam parameters will first of all be achieved by feed forward techniques, i.e. beam and magnetic measurements on one acceleration cycle and then incorporation of the necessary trims into the power converter functions. In case the reproducibility of the machine is not good enough to comply with tight tolerances an online feedback on magnetic correction elements has to be implemented. It should be noted that none of the big present hadron storage rings make operationally use of an online feedback on tune, chromaticty or coupling. The implementation of online feedbacks demands an effort on two additional fronts: The design of the feedback itself taking into account the dynamic behaviour of all involved elements and secondly the design of reliable measurement systems, which deliver signals for the betatron tunes, chromaticities and eventually coupling, without the need of human interpretation of the results.

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