MEASUREMENTS OF TUNE SHIFTS WITH AMPLITUDE AT THE ESRF

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Abstract

Together with the reduction of driving terms of third-order resonances, the minimisation of tune shifts with amplitude is an important lattice design issue for synchrotron light sources. Since the beginning of ESRF operation, the tuning of harmonic sextupoles has been further refined to better match this objective and improve machine performance. The experimental detuning with amplitude has been determined from the analysis of turn-by-turn BPM measurements for several sets of sextupoles and compared with predictions from the model. The limitations arising from the different contributions to beam decoherence, from non-linear beam dynamics… are discussed.

1 MOTIVATION

The search for a large dynamic aperture is a key feature for third generation light sources like the 6 GeV ESRF with a view to maximising the beam lifetime. The strategy for enlarging the dynamic aperture calls for small tune shifts with amplitudes to avoid driving particles onto destructive resonances.

Till recently, the optimisation of sextupole tuning was only based on tracking computations on the modelled optics. The recent installation of the turn-by-turn BPM system [1] allows the detuning with amplitude predicted from tracking computations on the modelled optics to be compared with experimental results.

The measuring technique consists in exciting a coherent horizontal oscillation of increasing amplitude with a single kick and recording the centre of charge position of the beam over 1000 consecutive turns. The 1 µs kick is provided by one of the injection kickers operated at 10 Hz repetition frequency.

The comparison of tracking results and experimental data is affected by a number of difficulties:

i) Tracking uncertainties due to the very non-linear transverse motion and to the deviations of the optics with respect to the ideal model.

ii) On the measuring side, many different damping mechanisms (chromatic modulation, tune shifts with amplitude, head-tail damping) add to the radiation damping (7 ms, i.e. 2500 turns) and spoil the signals.

2 TRACKING

Due to the very strong sextupoles needed to overcompensate the chromaticity, the particle motion is very non-linear and the classical quadratic dependence of tunes on betatron amplitudes (see Eq. 1) is not applicable.

$$\upsilon = \upsilon_0 + \frac{\partial \upsilon}{\partial \varepsilon}\varepsilon = \upsilon_0 + \frac{\partial \upsilon}{\partial \varepsilon}\frac{x^2}{\beta} \quad (1)$$

Tracking has to be used to determine the equivalent invariant with approximating data points by an ellipse (Fig. 1) as well as extracting tunes from an FFT of the tracked amplitudes. In addition to sextupole related non-linear behaviour, the errors (focusing + coupling) of the real machine also distort the phase space. In particular particles oscillating with large amplitudes can be trapped in resonance islands, as illustrated in Fig. 2.

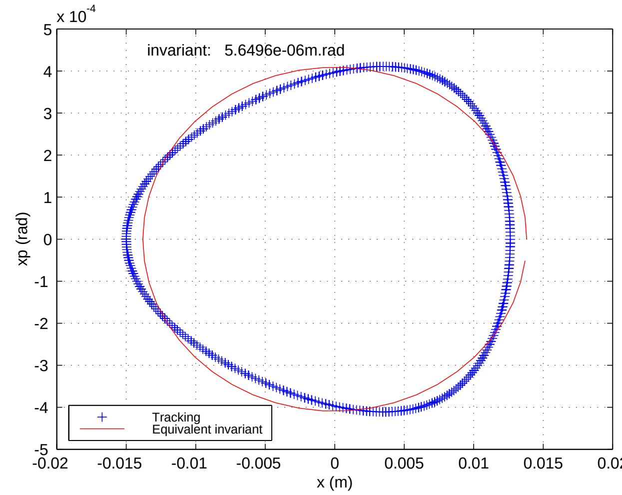

Figure 1: Phase space plot

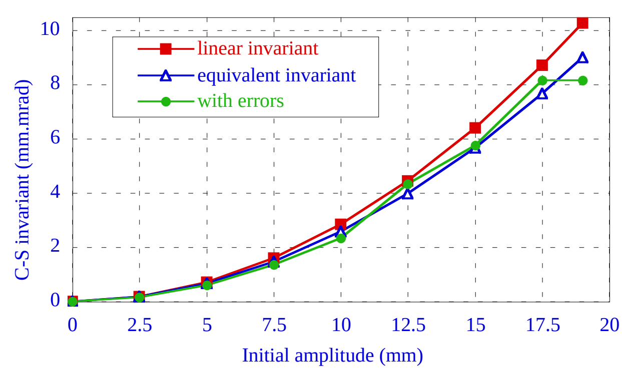

Figure 2: Comparison of Courant-Snyder invariants in different conditions

3 PROCESSING OF THE TURN-BY-TURN DATA

Turn-by-turn data are used to deduce the invariant value and the betatron tune from the oscillation of the beam following a single kick. This oscillation is damped by the synchrotron radiation damping, and by head-tail damping. In addition the coherent signal measured by the BPM decreases because of the decoherence of the beam resulting from the chromaticity and energy dispersion, and from tune shift with amplitude. We will therefore extract the information from a small number of turns immediately following the kick. In our measurements, the synchrotron radiation damping was neglected, and the head-tail damping was minimised by using a small bunch current (2.5 mA in 330 bunches).

3.1 Computation of the Courant-Snyder invariant

Beam position monitors are located at both ends of each of the 32 straight sections of the storage ring. This allows to obtain at the same time the beam position x and angle x' in the middle of each straight section. Over a number of turns N such that the decoherence and damping can be neglected, the corresponding phase space plot is a closed curve. We can approximate this curve by an ellipse and compute its parameters as:

$$\varepsilon_0 = \frac{1}{N}\sqrt{\sum_{n=0}^{N-1} x^2 \sum_{n=0}^{N-1} x'^2 - \left(\sum_{n=0}^{N-1} xx'\right)^2} \quad (2)$$

$$\beta_0 = \frac{\sum x^2}{N\varepsilon_0}, \quad \gamma_0 = \frac{\sum x'^2}{N\varepsilon_0}, \quad \alpha_0 = \frac{-\sum xx'}{N\varepsilon_0} \quad (3)$$

The invariant value is taken as the average of the emittance values in all straight sections. Once these initial parameters have been computed, we can deduce the invariant on each turn by assuming that the ellipse parameters are constant:

$$\varepsilon_n = \gamma_0 x_n^2 + 2\alpha_0 x_n x'_n + \beta_0 x'^2_n \quad (4)$$

3.2 Computation of the tune

To obtain the best accuracy on the tune value, we are using interpolated FFT with data windowing [2]. The beam position x_n is weighted with a Hanning window:

$$w_n = \sin^2\left(\frac{\pi n}{N}\right) \quad (5)$$

The Fourier coefficients are given by:

$$\phi_k = \frac{1}{N}\sum_{n=0}^{N-1} x_n w_n \exp(-2\pi jnk) \quad (6)$$

The tune values are obtained par interpolation between the two highest values ϕ_k and ϕ_{k+1}.

$$\nu = \frac{k}{N} + \frac{1}{N}\left(\frac{3\phi_{k+1}}{\phi_k + \phi_{k+1}} - 1\right) \quad (7)$$

The tune value is computed independently on each BPM, the average value is taken, and the standard deviation is an estimate of the accuracy of the computation.

4 DECOHERENCE DUE TO CHROMATICITY

After a transverse kick excitation, individual particles oscillate at slightly different betatron frequencies depending on the chromaticity $\xi = \frac{(\Delta\nu/\nu)}{(\Delta p/p)}$. The frequency mixing leads to a modulation of the signal at the synchrotron period.

The evolution of the betatron invariant with time is deduced from BPM data with Eq. 4 and is measured while varying the horizontal chromaticity from 0.3 down to –0.095. For each chromaticity, the intensity is varied so that the influence of head-tail damping is changed.

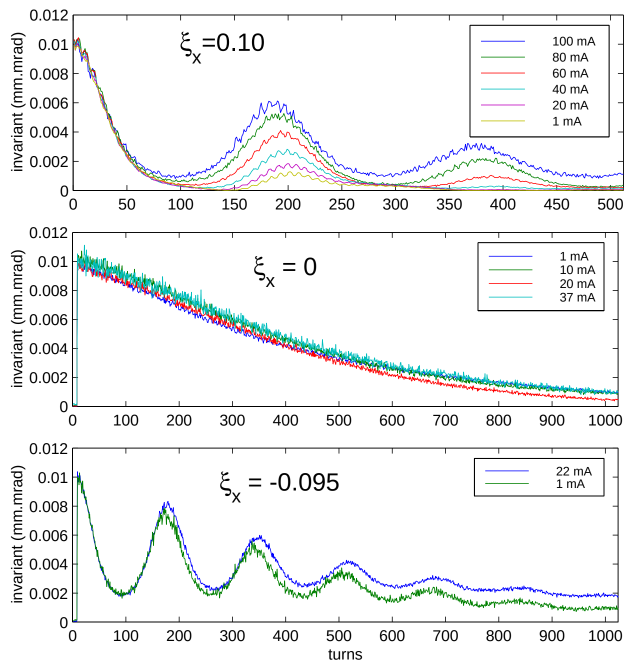

Figure 3: Measured betatron invariant as a function of number of turns for varying chromaticity and current

As shown in Fig.3, the initial damping is independent of intensity, which indicates that the chromaticity effect is dominant. The amplitude and time of the following recombinations depend on the intensity, showing the influence of head-tail damping. A "coherence time" was arbitrarily defined as the number of turns for which the invariant is larger than a given fraction of the initial value (we used 20% and 60%). Figure 4 shows that this coherence time is inversely proportional to the chromaticity.

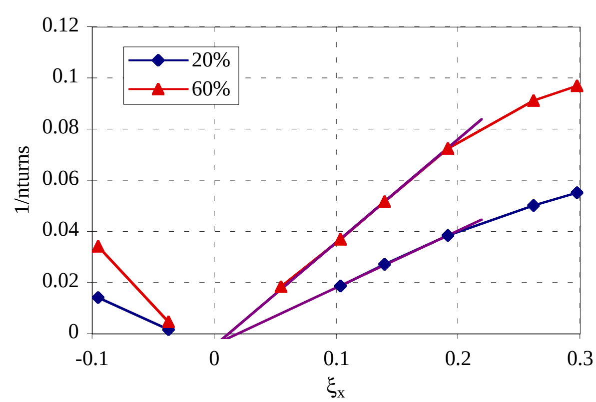

Figure 4: Decoherence as a function of chromaticity

5 DECOHERENCE DUE TO AMPLITUDE-DEPENDENT TUNE SHIFTS

Even if the optimum sextupole settings yield non-harmful tune shifts from an operational point of view, the tune spread within the particle distribution leads to beam filamentation within a small number of turns.

The detuning can be changed by acting on harmonic sextupoles while keeping the chromaticity constant and the dynamic aperture as large as possible. The machine was tuned with three different sextupole settings characterised by decreasing detuning (Table 1).

Table 1: Predicted horizontal detuning with amplitude for three different sextupole settings

	Tuning 1	Tuning 2	Tuning 3
$\frac{\partial \nu}{\partial \varepsilon}(10^4 * m^{-1})$	-3.39	-2.59	-1.11

In order to minimise other damping effects, the machine was run at low current per bunch and at zero chromaticity in both planes. The kicker was fired with the same amplitude. Figure 5 shows that the coherence of the signal increases with decreasing detuning.

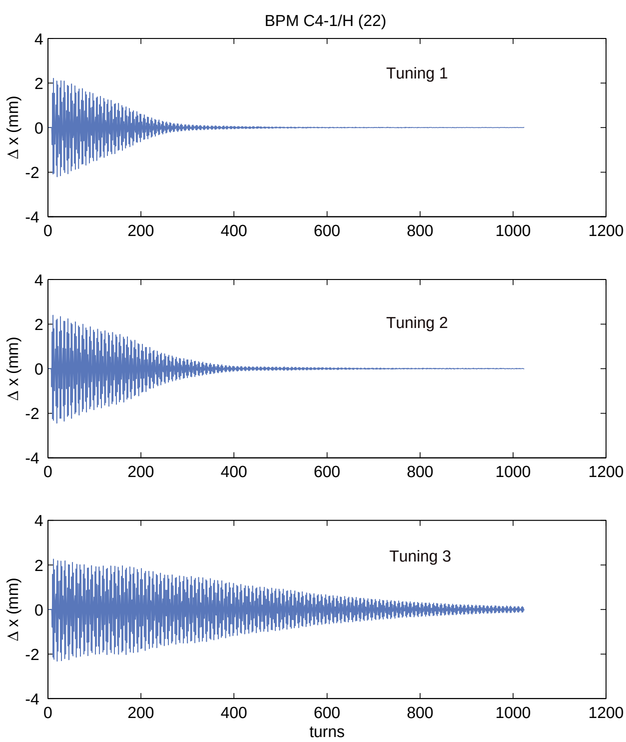

Figure 5: Evolution of decoherence with sextupole tuning

6 TUNE SHIFTS WITH AMPLITUDE

The horizontal detuning with amplitude was extracted from the turn-by-turn measurements for the different sets of sextupoles when running the machine at zero-chromaticity in both planes and low current per bunch. Measured tune shifts with amplitude are compared with predicted values in Fig. 6. The machine model used in the tracking code is generated from the analysis of the measured orbit response matrices [3] (with coupling and focusing errors experimentally minimised by resonance correction) and beam-based sextupole calibration [4].

Although the predicted detuning is larger than the measurements, there is a reasonable good agreement between measured and predicted tune shifts with amplitude. As already mentioned, the approximation of both experimental and computed phase space data by an ellipse is doubtful, given the very non-linear transverse motion, even at small amplitudes. Predicted tune shifts with amplitude strongly depend on the calibration of the machine model. A small change in the calibration of sextupoles relating strengths and currents (modifying for instance the assumed sextupolar component in the bending magnets) could be responsible for the over-estimation of theoretical tune shifts with amplitude.

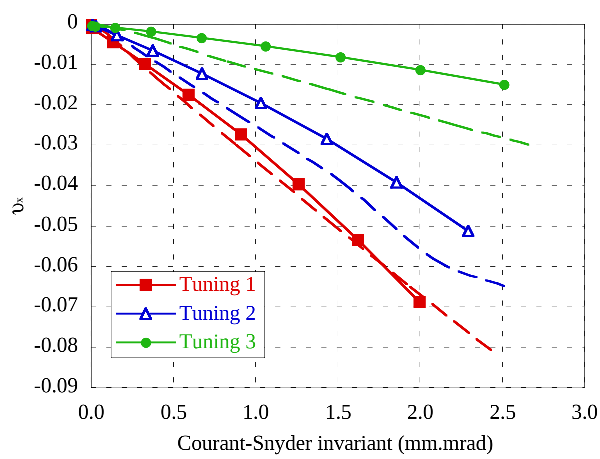

Figure 6: Comparison of measured (plain line) and predicted (dashed line) tune shifts with amplitude

7 CONCLUSIONS

Measurements of tune shifts with amplitude are made difficult by the rapid damping of the transverse signals. As for tracking predictions, the very non-linear transverse motion yields an additional difficulty. Nevertheless, the good agreement between predicted and measured detunings with amplitude obtained for different sextupole settings shows that the model representing the real lattice looks realistic and can be used for a better understanding of the beam dynamics.

8 REFERENCES

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