MEASUREMENT OF LATTICE PARAMETERS WITHOUT VISIBLE DISTURBANCE TO USER BEAM AT DIAMOND LIGHT SOURCE

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Abstract

With refined lattice tuning it becomes increasingly important to monitor or feedback on many parameters to keep stable optimum operating conditions. To this end we present techniques to measure betatron tune, chromaticity, betafunction magnitude/phase, and orbit response matrices all in such a way that no disturbance to the stored beam can be observed by the users of the light source. Examples of measurements for the various categories are compared to established methods, and their use in feedback schemes is discussed.

INTRODUCTION

Many measurements of lattice parameters require an excitation or change in setting that typically leads to a change in the beam position or shape. That is not acceptable during user operation in a synchrotron light source, where positional/angular stability to a fraction of a beam size/divergence is paramount (integrated motion of 10% of beam size/divergence up to 100Hz has often been quoted [1] as acceptable, but the demands are often even lower today):

- Measurement of betatron tune requires excitation of beam oscillations with a broadband signal. This is typically a kick, sweep/chirp or broadband noise delivered to the beam through a stripline or similar device. This leads to a blow up of the emittance for the duration of the excitation and following decay of the oscillations.
- Measurement of chromaticity usually requires measurement of the betatron tune at different stored beam energies. This is usually accomplished by changing the main RF frequency, which displaces the beam to a dispersive orbit in addition to the repeated blow up of the emittance from the repeated tune measurements.
- Orbit response matrix measurement requires changing of each corrector magnet one at a time and measuring the resulting differences in orbit. Again, this leads to displacements of the orbit which are many times the beam size. Furthermore, a complete response matrix measurement will take many minutes due to the large number of correctors typically present.
- Measurement of betafunction magnitude and phase is most often derived from a full orbit response matrix measurement.

On the other hand, the demand for regular measurements of all these parameters is increasing as refined tuning of machines requires continuous monitoring or feedback schemes. For example, the precise betatron tune decides the lifetime and injection efficiency, but it will vary with changes in insertion devices (IDs).

We have developed techniques which allow to perform these measurement with no visible disturbance to the user beam by either only exciting a small fraction (one bunch in a train of typically 720) for the tune measurement, or by exciting with small amplitudes (less than beam size) at high frequencies (only leads to an insignificant 'smearing' of the beam) and detecting these small signals with dedicated signal processing of longer durations. The trade off between small amplitude and longer observation time has allowed maintaining resolution at a level comparable to the standard techniques.

Common Principle of Excitation and Detection

The common principle shared by all the discussed applications is the injection of a small, sinusoidal disturbance, which is then measured by digital I/Q detectors which share the same time/frequency base as the excitation. In this way we are able to measure magnitude and phase of the response in a similar way as a lock-in amplifier does. In the following sections we will discuss the technical details of the implementations and show example measurements.

BETATRON TUNE MEASUREMENT

For the betatron tune measurement we excite the beam at a frequency near the nominal tune using a numerical oscillator (NCO) in the transverse multibunch feedback (TMBF) [2]. The beam motion is then detected in the same device by multiplying each bunch position with a

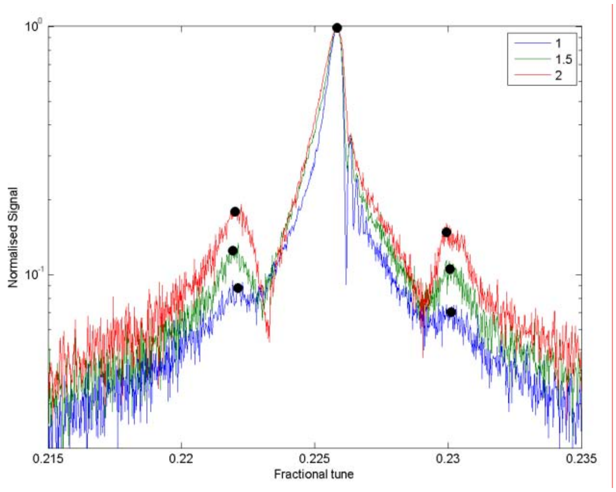

Figure 1: Horizontal betatron tune spectra for chromaticities 1, 1.5 and 2

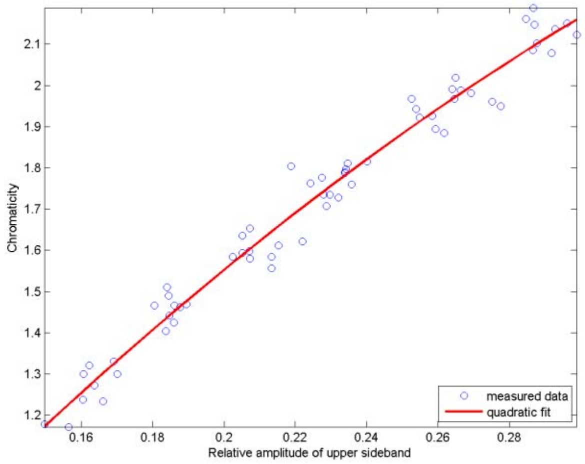

Figure 2: Measured chromaticity (by changing stored beam energy) and observed relative amplitude of a synchrotron sideband.

sine and cosine of the excitation frequency and accumulating the result for a certain period (we use 100 turns or 180µs). The frequency is then incremented by a small amount, and the process repeated for 4096 different frequencies, thus completing a sweep in less than 1 second. To operate the excitation in conjunction with the transverse multibunch feedback and to minimise the disturbance to the beam, we normally excite only one bunch, while the feedback operates undisturbed on all others.

The whole excitation and detection process is fully automated and implemented in the feedback FPGA, which delivers waveforms of I and Q per frequency point through to the EPICS driver. Inside the driver software, the sum of squares is computed and a simple peak find algorithm determines the actual betatron tune. Typical measurements of tune spectra acquired by this method can be seen in Figure 1.

CHROMATICITY MEASUREMENT

While it could be argued that the betatron tune can be more elegantly measured using a PLL that tracks the tune, the advantage of the swept excitation approach is that it also produces information about the synchrotron oscillation sidebands to the tune. From the intensity of these sidebands relative to the main line, the chromaticity can be derived. Figure 1 shows three example tune spectra for different chromaticities; the black dots indicate the peaks that have been identified by our peak search algorithm. We attempted to model the relative intensity of these peaks as described by other authors [3,4], but did not find a satisfactory fit with our observation. In the end, a measurement of the relative sideband intensities during controlled variation of the chromaticity (as measured with the standard approach of varying beam energy by changing the storage ring RF frequency) was used to create an empirical fit with a polynomial (see Figure 2). This function is now subsequently employed to give a measurement of the chromaticity from the tune spectrum available every second.

The fitting routines to identify the relative peak intensities and the empirical model to compute the chromaticity from these are current implemented in a MATLAB routine which can operate either on live tune or archived tune spectra.

BETAFUNCTION MAGNITUDE AND PHASE

Whereas the measurement of betatron tune (and the chromaticity measurement derived from the tune spectrum) required only excitation and detection in a single location in the storage ring, a measurement of betafunction requires measurement at as many locations as possible. We have used all 168 BPMs with their turn by turn (TbT) measurement capability, while exciting oscillations of the beam at betatron frequency. It is important to trigger the acquisition of TbT data synchronously on all BPMs, so that magnitude and phase of the oscillations can be computed.

With the frequency of the oscillation precisely known, the TbT data is analysed by an extension to the BPMs' EPICS driver by multiplication with a cosine/sine and accumulation over the whole stored TbT waveform with up to 2^{19} turns (equivalent to about 1 s of data with our revolution frequency of 533820 Hz). It should be noted that this upstream processing leads to massive data reduction, as we produce only one orbit reading of magnitude and phase per trigger instead of >700MB of TbT data per second from all BPMs.

The I/Q detector with accumulator over 1 s can be regarded as equivalent to a 1 Hz spectral filter on the betatron frequency, so a tight locking of time/frequency bases between the excitation (in our case the NCO in the TMBF) to the acquisition (in our case the sample clock in the BPMs) is required. We achieve this as the NCO in the

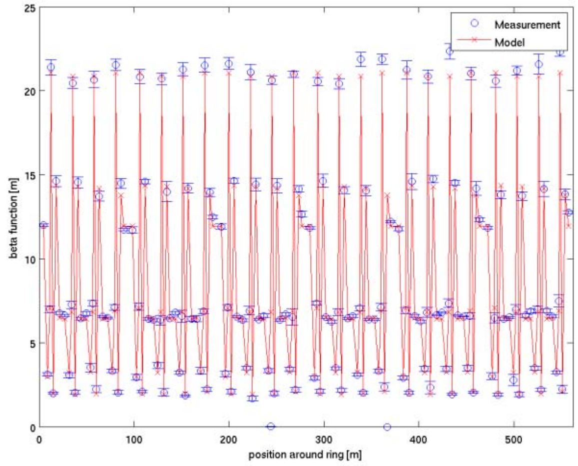

Figure 3: Measured and model beta function magnitude

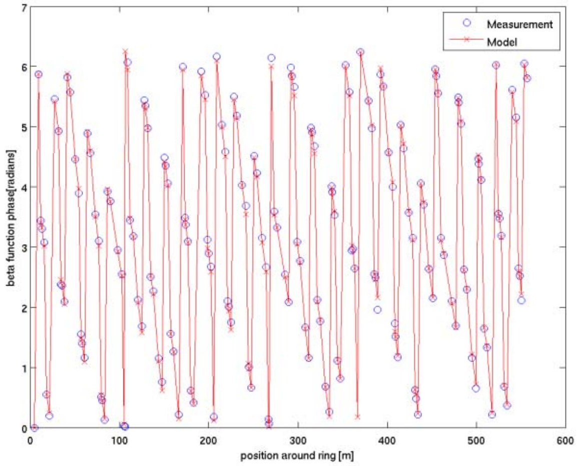

Figure 4: Measured and model beta function phase

TMBF is clocked directly by the storage ring RF frequency, while the sample clock in the BPMs is locked to the revolution clock, which is generated by division from the RF frequency.

Figure 3 shows an example measurement with an amplitude of 0.5 to 2.5 µm (depending on beta), and 9 sets of data taken from 2^{17} turns each. From the 9 sets the mean and standard deviation have been calculated and used to generate the error bars in the plot (the error is the 'predicted error' on the mean, ie 1/3 of the standard deviation of the 9 measurements). Despite the small amplitude this measurement is in excellent agreement with the model and within the expected beta beat of 10%.

Figure 4 shows the beta function phase retrieved from one of the sets of the same data. Both magnitude and phase data are of sufficient quality to allow permanent monitoring of the sanity of the optics.

CORRECTOR ORBIT RESPONSE

While all measurements presented so far used an excitation at or near the betatron frequency and using a stripline to kick the beam, we can also inject a low frequency into one corrector magnet and observe the response on all BPMs. For these lower frequencies and to the benefit of resolution, the recorded data should cover several seconds of orbit observation. On the other hand, TbT time resolution is not required, so we record the 'Fast Acquisition' data stream which is at 10072 samples/s in our case.

To ensure we are reading all BPMs synchronously we tap into the Communication Controller network which we use for the Fast Orbit Feedback (FOFB) using an additional listener node. The FOFB processing nodes are used to inject the disturbance by adding a sine wave of programmable amplitude and frequency generated from a shared time base into any of our 168 corrector magnets per plane. The excitation and measurement can take place even with the FOFB running at the same time by choosing a frequency high enough to be outside the effective bandwidth of the FOFB.

The additional listener node is capable of receiving the full stream of orbit data at 13.5 MBytes/s which it record to hard disk for later analysis. At the moment, we use 10s recordings and analyse these in MATLAB, but it is planned to move the processing into the listener node, to achieve the necessary data reduction that would simplify continuous observation.

We have tested the accuracy and repeatability of a measurement with one corrector excited at 200Hz by comparing it to the model corrector response and the response taken by the traditional method of stepping the corrector magnet and recording orbits before and after. It should be noted that the measurement results of the 200Hz excitation shown in figure 5 have been scaled to fit the model best, as currently the roll off of the magnet/vessel/power supply is not taken into consideration. Other than that the measurements are of excellent reproducibility and identify the same apparent mismatch between the actual storage ring behaviour as seen by the step change.

With respect to the resolution of the measurement, it should be taken into account that even the excitation amplitude is about 10 times less than typically used when the corrector is stepped and thus the resulting orbit changes are only in the order of 17µm RMS compared to 170µm RMS with the step change. On the other hand, the orbit is observed for 10s instead of 100ms, and consequently noise is picked up from a 100 smaller bandwidth, theoretically improving the resolution on the orbit measurement by a factor of 10, so that the reduced amplitude and extended measurement time should cancel out.

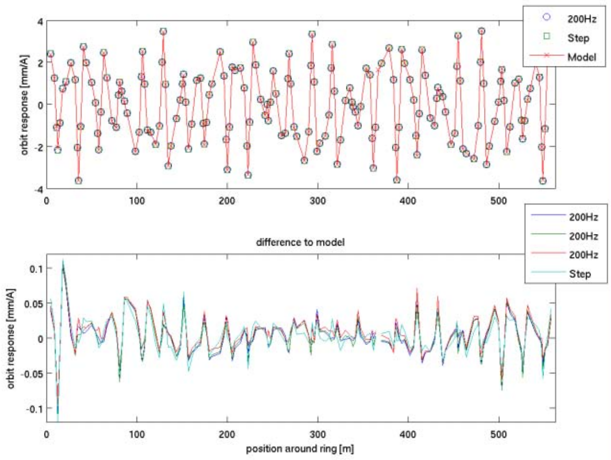

Figure 5: Corrector orbit response, measured by excitation at 200Hz and by step changing the corrector, as well as model response. The lower plot shows the difference to the model of three repeated measurements at 200Hz and one step change

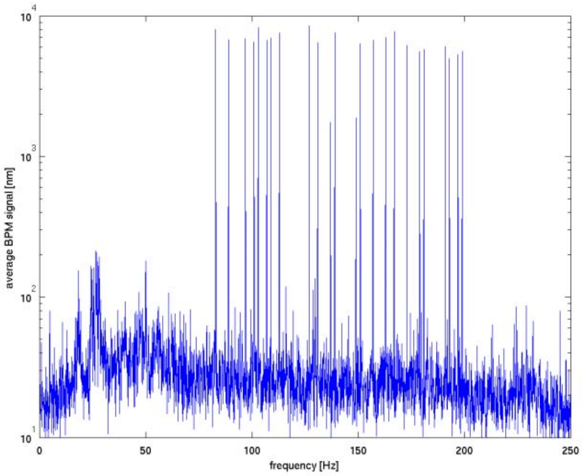

Figure 6: Beam motion spectrum averaged over all 168 BPMs during excitation with 24 frequencies on 24 corrector magnets.

Simultaneous Measurement of Excitation with Multiple Correctors

Measuring a whole corrector response matrix one by one spending 10s to observe each corrector would require about one hour of time for our 168 correctors in 2 planes. However, it is possible to excite several correctors at the same time using different frequencies, and then observe their response simultaneously by 'tuning in' on the respective frequencies. We have tried this with excitation of 24 correctors and we have chosen the 24 highest prime numbers below 200Hz as excitation frequencies to avoid any harmonic contamination of the measurements. The average beam position spectrum of all BPMs is shown in figure 6, and the 24 corrector responses compared to the model are shown in figure 7. The difference between the model and the measurement is likely to be due to a real mismatch between the machine and the model, rather than random or systematic errors in the measurement.

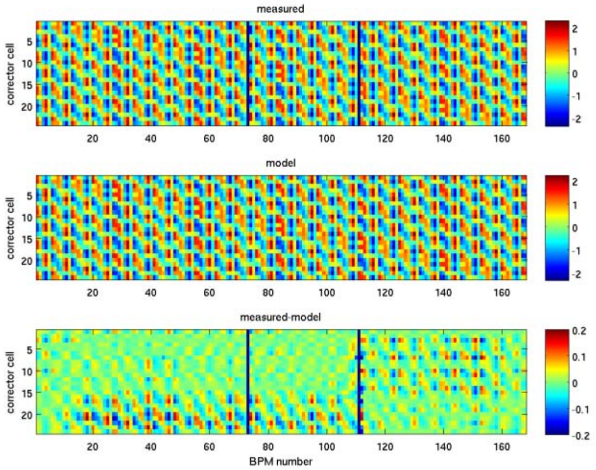

Figure 7: Partial orbit response matrix retrieved from simultaneous excitation of 24 corrector magnets, compared to the model response

For the measurement of the whole corrector response matrix there is a choice of either repeating measurements with a subset of correctors excited, or theoretically one could also excite all correctors at the same time with different frequencies. Furthermore, instead of different frequencies more complex signals which are orthogonal to each other could be chosen, for instance pseudo random codes [5]. This would have the further advantage that the disturbance is spread in spectrum and would appear just like a slight increase in the noise floor.

SUMMARY

Using the presented methods we are able to measure lattice parameters by injection and detection of a perturbation that is small compared to the beam size and thus practically invisible to light source users. The presented methods use different sources of excitation and different diagnostics systems for detection (see table 1), but they all share the common principle of injection of a single tone and phase locked detection at the same frequency.

While some of the methods are in regular use or ready to be used, further study and optimisation will be required in particular for the corrector response matrix measurement with multiple excitations in parallel. Experiments with a deliberate distortion of the storage ring optics should prove the ability to identify that.

Table 1: Systems used for excitation and detection in the four measurements and status of implementation

Measurement	Excitation	Detection	Status
Tune	Stripline TMBF	TMBF	in use
Chromaticity	Stripline TMBF	TMBF MATLAB	ready for use
β mag/phase	Stripline TMBF	EBPMs TbT data	ready for use
Corrector response	Corrector FOFB	EBPMs FA data	first tests

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