CALIBRATION OF THE NONLINEAR ACCELERATOR MODEL AT THE DIAMOND STORAGE RING

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Abstract

The correct implementation of the nonlinear ring model is crucial to achieve the top performance of a synchrotron light source. Several dynamics quantities can be used to compare the real machine with the model and eventually to correct the accelerator. Most of these methods are based on the analysis of turn-by-turn data of excited betatron oscillations.

We present the experimental results of the campaign of measurements carried out at the Diamond. A combination of Frequency Map Analysis (FMA) and detuning with momentum measurements has allowed a precise calibration of the nonlinear model capable of reproducing the nonlinear beam dynamics in the storage ring.

INTRODUCTION

The Diamond storage ring has been operating for users since January 2007 [1]. The linear optics of the machine was successfully implemented during commissioning using the LOCO package [2]. The beta-beating is routinely corrected to 1% peak-to-peak or less and the linear coupling can be reduced to less than 0.1% if required [3-4].

A campaign of measurements was set up to understand the nonlinear dynamics of the beam in the storage ring. The operational drivers for this activity are the understanding and the improvement of the injection efficiency, the Touschek lifetime and the beam losses around the ring. A necessary step of this investigation is the determination of a reliable model of the nonlinear beam dynamics.

The improvement of the nonlinear machine model has been a continuing and still ongoing process: on the one hand all available measured magnetic components of each individual quadrupole and sextupole have been introduced into the model, albeit for the dipole field we were forced to rely on the measurement of a single prototype. On the other hand we have gathered a large wealth of measurements of dynamical quantities that provide information about the nonlinear model of the storage ring. The strategy is to modify the model such that each of the measured dynamics quantities is reproduced. The claim is not that the real model is determined but rather to find an effective model which can be used to further understand and control the effect due to the nonlinearities of the system. The dynamical quantities to be used are the chromaticities, the detuning with amplitude, the dynamic aperture, the frequency maps and the resonant driving terms and the Touschek lifetime. In this paper we present the results of the model calibration made using nonlinear chromaticitites, dynamic apertures and frequency maps.

Diamond is equipped with the necessary hardware to perform an advanced investigation of the nonlinear beam dynamics. Various means to excite betatron oscillations are available: pinger magnets which give impulsive kicks to the stored beam and striplines which provide a continuous resonant excitation (albeit at small amplitudes). A crucial component is a well understood systems of highly performing turn-by-turn BPMs. In particular, a correct understanding of the Frequency Maps and of the resonant driving terms depends critically on the proper reconstruction of the betatron oscillation from the turn by turn BPMs data. Significant improvements in the modelling were made after a series of unsuccessful comparison pointed out a number of subtleties in the BPMs response to the betatron oscillations which required careful consideration and correction.

In this paper we first describe the progress made in the calibration of the nonlinear model by fitting the detuning with momentum, the detuning with amplitude and using the information provided by the frequency maps. Then we will review the issue met in the correct reconstruction of the betatron oscillations from the turn by turn signals acquired at all BPMs.

MEASUREMENTS AND MODELLING

The simplest dynamical quantities that characterise the nonlinear beam dynamics are the chromaticitites and the detuning with amplitudes. At Diamond it is possible to detect the tune dependence with momentum deviation by varying the RF frequency of the machine. The relation between a change of the RF frequency to the momentum deviation is made complicated by the higher order terms in the expansion of the momentum compaction factor with off-momentum deviation, nevertheless it was possible to explore a range of off-momentum deviation sufficient large so as to put into evidence the higher order chromaticities components.

The dependence of the betatron tunes on the off-momentum deviation and on the amplitude were used as target vectors for a fit of the sextupole families values. This technique was first used in [5] to optimise numerically the detuning with off-momentum deviation in the design stage of the Diamond storage ring. We build a vector whose components are the betatron tunes at a selected number of off-momentum points, then we append to the same vector the betatron tunes at a selected number of amplitudes in x and y. In this way we obtain a target vector that we can measure on the real machine and at the same time can be computed on the model. The differences between these two vectors are used to make a least square fit of the sextupole gradients. The structure of the target vector has to be defined with a trial and error approach and it is likely to be machine dependent. For diamond we found that a target vector which has betatron tunes at ±1% energy deviation and ±1 mm amplitude deviation in H and V was adequate, achieving convergence of the fit and a reasonably good match between model and experimental data. In this way we have built a vector with eight points and fit the eight sextupole families of the diamond storage ring. The result of the final matching on the detuning with momentum is reported in Figure 1.

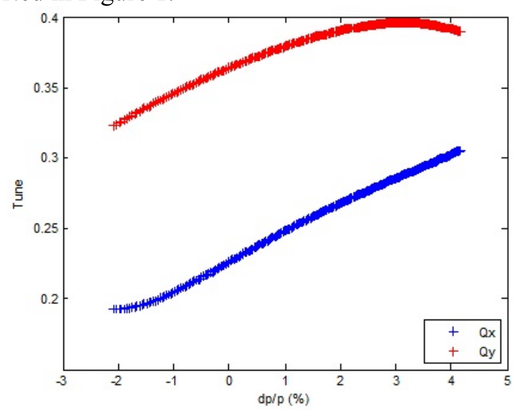

Figure 1: detuning with momentum: measured (crosses) model (continuous line barely visible below the crosses).

The matching of the non linear chromaticity is particularly good. This was achieved with a variation of the sextupole gradients which are within 2 percent. While this value appears to be high with respect to the measurement errors of the sextupole gradient, a careful re-analysis of the calibration tables of the sextupole gradient is in progress. Another possible source of discrepancy is the lack of agreement with natural chromaticity in the V plane which is then redistributed among the gradients of the various sextupole families. The assessment of the effect of the sextupoles on the chromaticity in fact requires a proper understanding of the natural chromaticity.

With this respect careful measurements were done by measuring the natural chromaticities shifting the main dipole field and using a Hall probe in the dipole magnet to measure the relative magnetic field variation. This produced a good agreement of horizontal natural chromaticity ($\xi_{x0} \sim -79$) while still few units were unaccounted for in the vertical natural chromaticity. We measured $\xi_{y0} \sim -31$ while the ring model using hard edge dipoles provides $\xi_{y0} \sim -33$. The hard edge model with the 1/(1+dp/p) correction [6] produces $\xi_{y0} \sim -35$. The model which uses the exact Hamiltonian and dipole fringe field described to second order symplectic integrator in MAD-X PTC module [7] provides $\xi_{y0} \sim -35$. In this last case the product FINT*Hgap was set to 0.03 to best match the longitudinal roll off of the dipole field. The quadrupoles were re-fit to correct the linear optics to account for the extra linear focussing provided by the finite extent fringe fields. We found that varying FINT*HGAP does not produce a significant change in the natural chromaticity after refitting the linear optics. The origin of this discrepancy is still under investigation: it is believed that a more careful description of the magnetic field in the dipole is required.

The results of the fit obtained with the target vector that combines detuning with momentum and detuning with amplitude have been checked a posteriori with the analysis of the FM. The resulting discrepancies have suggested us the use the FM itself to calibrate the higher order errors in the nonlinear model. In particular the analysis of the FM has allowed the identification of an excessive contribution to the normal octupole component in the main dipole which is responsible for significant variation in the extension of the frequency map. The normal octupole component initially used in the model comes from the main dipole measurement of a single prototype and was initially assumed as a systematic error in all the dipoles. This assumption produced an unrealistically large detuning with amplitude and a wide frequency map. Using the normal octupole component of the main dipole as a fit parameter, we finally achieve a very good agreement of the frequency maps and measured dynamic aperture as shown in Figures. 2-4.

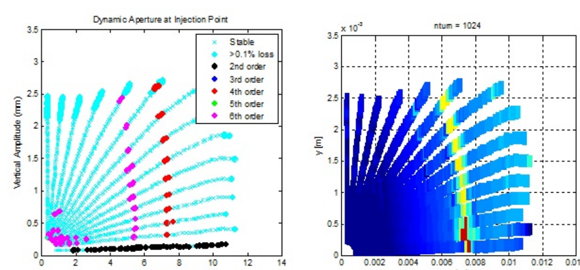

Figure 2: Dynamic aperture and resonance lines plotted in the (x, y) plane: measured (left) and model (right).

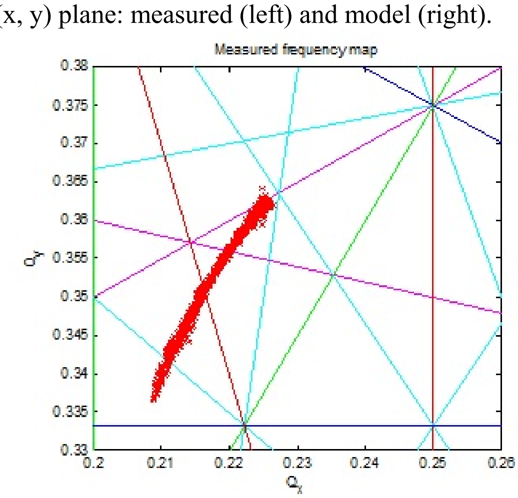

Figure 3: measured FM for the Diamond storage ring.

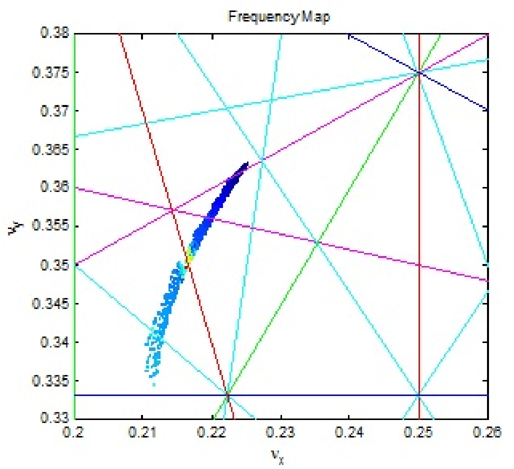

Figure 4: model FM for the Diamond storage ring

BETATRON OSCILLATIONS FROM TURN BY TURN BPMS DATA

In order to reconstruct correctly the betatron oscillation from the turn-by-turn data signal a number of correction to the beam data have to be applied.

First of all we correct for the linear coupling between the electronic channel and any possible rotation of the BPMs by using the coupling matrix provided by LOCO. This is the result of the fit of the cross talk between the X reading and the Y reading. LOCO provides for each BPM a 2x2 matrix that decouples the data from the residual coupling in the BPMs.

When investigating large amplitude oscillations the geometric nonlinearities of the BMPs have to be taken into account. To this aim we used a numerical procedure, proposed in [8], for the inversion of the nonlinear response of the four BPM buttons of the BPM to the (x, y) position of the beam inside the BPM block. Further investigation of this method at Diamond has put in evidence how this approach is superior to the Taylor expansion in the (x, y) plane of the BPM response based on the four button signal [9]. In particular it was highlighted that this approach removes the issue related to the relative offset of the BPM blocks to the reference orbit, which can generate spurious spectral lines if a simple 2D Taylor series approach is used.

Another important aspect of the response of the BPMs to an excited betatron oscillation concerns the filter used to generate the BPM signal corresponding to a given turn from the ADC samples. The filter used is a characteristic of the BPM electronics hardware and firmware. The signal at a given turn is computed from the digitised samples provided by the BPM which produce 220 points within a turn (17 MHz sampling). To reduce this higher sampling rate to the turn by turn rate while fulfilling the Nyquist criteria and minimising out of band noise, the impulse response of the filter has to extend over the neighbouring turns so that the actual signal ends up containing some information on the position of the beam in the neighbouring turns. If careful synchronisation of the BPM acquisition and the fill pattern is used, the resulting impulse and frequency response can be precisely calculated as reported in Figure 5. It shows clearly that the BPM response to an excitation with fixed amplitude depends significantly on the tune value.

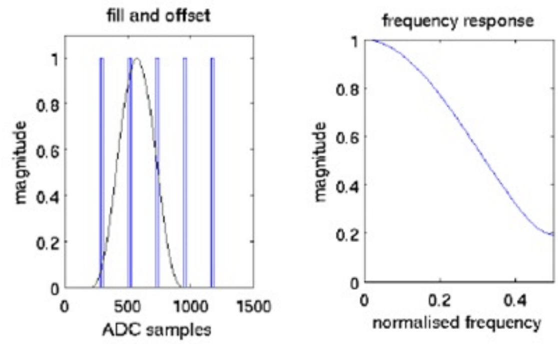

Figure 5: Time filter (left) and corresponding frequency response of the BPM (right).

This aspect was crucial in assessing correctly the amplitude of the betatron oscillations and it ultimately allowed a successful fit of the detuning with momentum and detuning with amplitude as described. Lastly we notice that the alignment of the time filter depends on the location of the BMP in the ring to take into account the time of flight of the beam between the various BPMS. It also depends slightly on the fill pattern used in the experiments. These effects, however, can be deconvoluted from the original BPM signal to provide the actual betatron oscillations of the beam.

CONCLUSIONS AND ACKNOWLEDGMENTS

We have presented the latest result in the analysis of the nonlinear beam dynamics at the Diamond storage ring. We have proven that the analysis of the nonlinear chromaticity and of the frequency map can provide very important information about the nonlinear model of the storage ring. We plan to continue the refinement of the nonlinear model by complementing the information acquired with the data obtained from the analysis of the resonant driving terms to provide and effective model of nonlinear beam dynamics.

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