PROGRESS WITH UNDERSTANDING AND CONTROL OF NONLINEAR BEAM DYANAMICS AT THE DIAMOND STORAGE RING

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Abstract

The Diamond light source started operation for users in January 2007. With the successful commissioning of the nominal optics, delivering a 2.75 nm emittance beam at 3 GeV, we now routinely provide the users with a 250 mA beam with a lifetime of 20 h, exceeding the minimum specified current-lifetime product of 3000 mAh.

Driven by the necessity to guarantee a correct implementation of the nonlinear optics, a significant experimental and theoretical effort is ongoing to understand and improve the nonlinear beam dynamics in the storage ring. The necessity to control the nonlinear beam dynamics is even more urgent with the installation of a large number of small gap (5 mm) in-vacuum insertion device and the need to control the injection efficiency with Top-Up operation. We report here the present status of the analysis of the nonlinear beam dynamics and the main experimental results.

INTRODUCTION

Diamond is a third generation light source which entered in operation in January 2007 [1-2]. The storage ring lattice is a Double Bend Achromat (DBA) where the achromatic condition is broken and dispersion leaks in the straight sections in order to reduce the natural emittance of the machine. The storage ring consists of 24 DBA cells, with ten quadrupoles and seven sextupoles per cell, making a total of 48 dipoles, 240 quadrupoles and 168 sextupoles. The sextupoles are combined function magnets which also have skew quadrupole and dipole correctors in the horizontal and vertical plane. These magnets all have independent power supplies, allowing a large degree of freedom in the choice of both the optimisation and the correction of the linear and nonlinear optics. The ring is also equipped with a set of 7 BPMs per cell providing a total of 168 BPMs, each with turn-by-turn capabilities.

The sextupoles were carefully optimised in order to provide sufficient dynamic aperture and momentum aperture for injection and a Touschek lifetime of at least 10 h for the nominal operating current of 300 mA in a 2/3 fill. Extensive numerical simulations were performed to ensure that the injection efficiency and the Touschek lifetime were maintained even with the complement of IDs planned for Phase-I and Phase-II. Currently this includes ten in-vacuum IDs at 5 mm minimum gap, two superconducting multipole wigglers and an APPLE II device. Two customised optics are also planned in two long straight sections, providing two vertical mini-beta sections with two virtual horizontal focuses.

Striving for the lowest emittance achieved so far in a medium energy machine (2.75 nm), the correct operation of the ring requires a very strict control of the optics of the storage ring. During the commissioning the correct implementation of the linear optics was achieved with the use of the LOCO package [3] and its implementation in the MATLAB Middlelayer [4]. The residual β-beating was reduced to less than 1% peak-to-peak and the nominal emittance of 2.75 nm was measured with very good correction of the linear coupling. The correction is achieved with LOCO by fitting the quadrupoles to match the model and measured orbit response matrix. The required quadrupole gradient corrections are below 2% peak-to-peak and are compatible with the measurements of the quadrupole gradient performed prior to the installation of these magnets.

While the correct implementation of the linear optics is nowadays not unusual in modern third generation light sources, the analysis and correction of the nonlinear model of the storage ring of most modern light sources still stops short of an equivalently good solution [5]. In this context, Diamond has put in place a significant experimental and theoretical effort to provide tools and strategies that allow a correct implementation of the nonlinear model of the storage ring. In this paper we report the current status of the investigation and the main experimental results.

CHARACTERISATION OF THE NONLINEAR BEAM DYNAMICS

The nonlinear dynamics of the storage ring is optimised in order to provide sufficient aperture for injection and adequate Touschek lifetime for the electron beam in the various operating conditions. This is achieved by extending the dynamic aperture and the momentum aperture of the ring. Numerical tracking is ultimately used to validate the optimisation and currently available codes such as Tracy-II [6] or elegant [7] have automated numerical computation of the ring apertures.

It is desirable however to provide dynamical quantities that characterise the nonlinear behaviour of the ring that can be used at the design stage, that can give insight on the beam dynamics and provide further guidelines to the optimisation. When these quantities can be accessed experimentally in the machine, they provide a valuable to tool to compare the nonlinear model of the ring with the real nonlinear behaviour of the beam in the storage ring. The dynamical quantities typically used are the detuning with amplitude and the nonlinear resonance driving terms, which can be computed to the desired perturbative order with codes such as Tracy-II and Mad-X/PTC [8]. A crucial problem in nonlinear beam dynamics is related to the fact that these quantities are not necessarily well correlated with the dynamic and momentum apertures of the ring which is the ultimate goal of the optimisation. It is well known that, in general, the dynamic aperture and the momentum aperture cannot be simply improved by targeting detuning with amplitude, one or even a few resonant driving terms. Therefore the optimisation has to be validated numerically. Nevertheless these quantities allow the comparison of the nonlinear model to the ring.

Another very interesting numerical tool that allows a quick analysis of the resonance net around the working point in the tune diagram is the Frequency Maps (FMs) introduced in accelerator physics by J. Laskar [9]. This allows drawing the region occupied by the beam in frequency space. The diffusion coefficients allow a clear visual understanding of the strength of a given resonance crossed by the beam. FMs can also be measured experimentally and the diffusion strength can be somehow substituted with the measured losses thus allowing a valuable comparison of the real machine with the model.

Finally, the measurement of the spectral lines of the betatron oscillations and their connection to the resonance driving terms [10-11] has been proposed to compare the behaviour of the real machine with the nonlinear model. The spectral lines can be associated with the amplitude and strength of a given resonance driving term and give a complementary handle to control the implementation of the model to the real machine.

FREQUENCY MAPS AND DYNAMIC APERTURE STUDIES AT DIAMOND

The nonlinear beam dynamics activity at Diamond has aimed at achieving a good implementation of the nonlinear model of the storage ring in order to guarantee sufficient injection efficiency and Touschek lifetime. Crucial to this work was the installation of two pinger magnets in Sept. 2007 and the possibility of acquiring turn-by-turn data from all BPMs in the ring. The pingers can independently kick the beam in the horizontal and in the vertical plane to large amplitudes, scanning the whole dynamic aperture available. They were used to determine the dynamic aperture (DA) and to measure the frequency map (FM) of the storage ring.

The comparison between the measured DA and the prediction from the model is reported in Fig. 1. Considering that the yellowish regions in the model DA are likely to be lost over long term tracking, we can only claim a qualitative agreement in the shape of the DA, especially in the horizontal plane. The measurements show a significant disagreement which reaches a factor two in the vertical plane. This degree of disagreement is not unusual, even for modern third generation light sources [5]: it points to the fact that our present knowledge of the nonlinear model does not fully capture the complexity of the nonlinear motion of the beam in the storage ring. In fig. 2 we report a measurement of the momentum aperture obtained from a scan of the lifetime as a function of the RF voltage, in a condition where the beam lifetime is Touschek dominated. Again the agreement is qualitatively good but the simulations fail to reproduce the exact voltage for which the maximum lifetime is attained. The model gives maximum lifetime for a voltage which is about 15% smaller than the measurements corresponding to 0.5% underestimate of the momentum aperture.

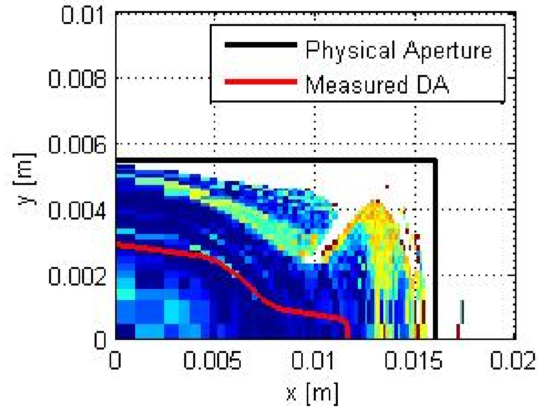

Fig. 1: Comparison of the measured dynamic aperture with the prediction from the model. The colour code illustrates the diffusion strength. Tracking is performed with Tracy-II.

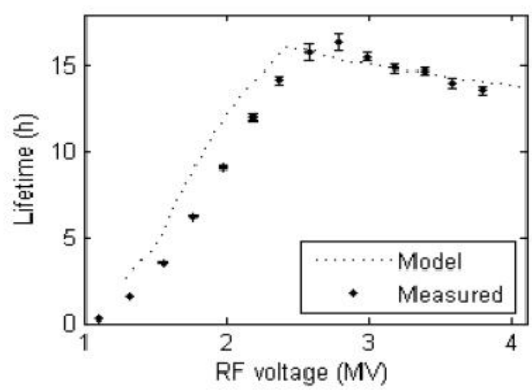

Fig. 2: Comparison of the measured and model lifetime as a function of the RF voltage.

The reason for this disagreement is still the object of investigation. On the one hand we are trying to include in the model all possible known error sources, on the other hand we are investigating the appropriate modelisation of the magnetic elements trying to include thick lense multipoles, fringe fields, edge focussing effects and their momentum dependence. In particular we have included a better description of the magnetic length of the magnets by using the individual data coming from magnetic measurements and we have introduced octuplolar components in the quadrupoles which was considered to be the main source of error. While these additional ingredients have improved the match between model and real machine, as shown later for the FMs, it is worth pointing out that even when including the best knowledge of the nonlinearities in the ring we still obtain slightly different values for the chromaticities which are (3, 1.5) in the model while we measure (2, 2) in the machine. Errors in the calibration tables for the sextupole magnets are also a possible source of disagreement between the machine and the model.

In Fig. 3 we report the measurements of the frequency map obtained by scanning the aperture with the pinger magnets and measuring the corresponding betatron tunes. In Figs. 4-6 we report the corresponding FMs obtained from numerical tracking in the model. Different refinements of the nonlinear model were used. Fig. 4 corresponds to the bare lattice with the nominal sextupole lengths. In Fig. 5 we used the correct magnetic length for the sextupoles obtained from magnetic measurements. Fig. 6 includes the octupolar errors in the quadrupoles. It is clear that a better description of the model improves the agreement but there are still significant deviations which are not explained. Work is ongoing to include all the remaining mutlipolar errors in the quadurpoles, the main errors in the dipoles and sextupoles and a better calibration table of the sextupole gradient.

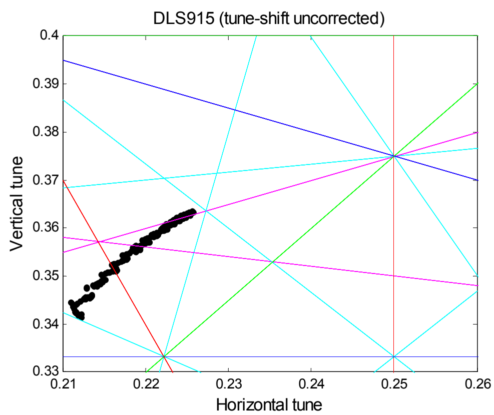

Fig. 3: Measured Frequency Map on the bare lattice without Insertion Devices.

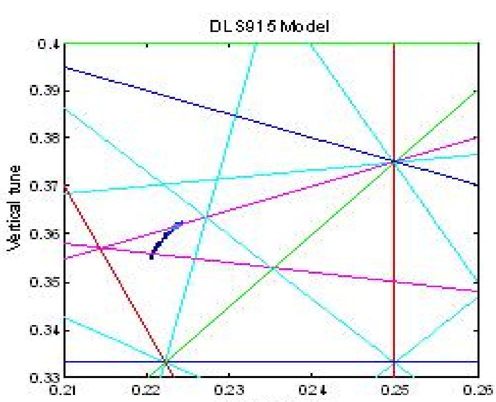

Fig. 4 Model Frequency map. Bare lattice without Insertion Devices.

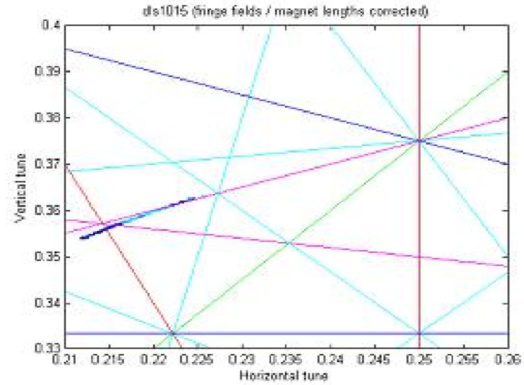

Fig. 5: Model Frequency Map as in Fig. 4, adding to the model the correct magnetic length of the sextupoles as per magnetic measurements.

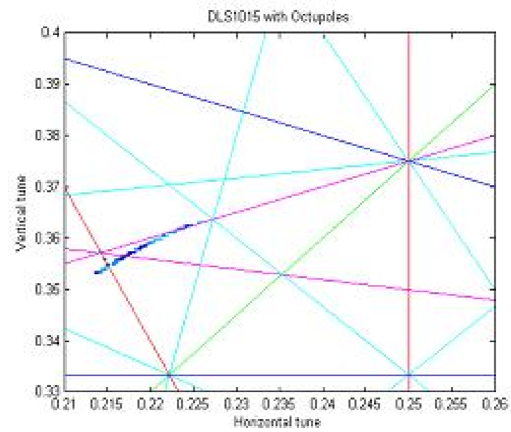

Fig. 6 Model Frequency map as in Fig. 5 adding to the model the octupolar errors in the quadrupoles as per magnetic measurements.

SPECTRAL LINES MEASUREMENTS

It has been shown in the past that Fourier analysis of the betatron oscillations can provide a wealth of information about the nonlinear dynamics of the beam in the storage ring [10]. The basic idea is to connect the amplitude and phase of the Fourier coefficients of the spectral lines with the amplitude and phase of the driving terms of a given resonance. A more complete investigation in the framework of the map pointed out that a full reconstruction of the nonlinear model is possible at least if turn-by-turn data with sufficiently high precision are available [11]. More recently a new algorithm has been proposed for the reconstruction of the nonlinear machine model based entirely on the comparison of the amplitude and phase of the spectral lines [12]. The model reconstruction has been demonstrated in tracking data and a first experimental investigation has show that it is indeed possible to correct simultaneously several resonance driving terms [13]. The procedure introduced in [12] mimics closely the approach that LOCO takes to correct the linear optics of the ring where the role of the orbit response matrix is taken by the Fourier coefficients of the spectral lines excited by nonlinear resonance driving terms, measured at all BPMs, and the role of the quadrupoles is now taken by the sextupoles. A fit procedure aims at defining the sextupole values which match the spectral lines measured on the machine with the one obtained from numerical tracking from the model. We have recently substantially improved the fit algorithm by taking into account the phase information by considering the real and the imaginary part of the spectral lines. When applied to tracking data this information allows a faster and more robust reconstruction. Its application to experimental data will be carried out in the near future.

Several experiments with pinged beams were performed at Diamond. They showed that the amplitude of the spectral lines related to nonlinear resonances can be measured with very good precision and corrected to restore the original pattern of the amplitude along the ring. In the experiment we targeted the amplitude of the $Q_x - Q_y$ spectral line measured in the vertical plane and the amplitude of the –2Qx spectral line measured in the horizontal plane. These are related to the driving terms of the resonances $Q_x \pm 2Q_y$ and $3Q_x$ respectively. We have verified experimentally that targeting a single spectral line can produce a good correction of the driving term as shown in Fig. 7. However this does not necessarily improve the DA and momentum aperture of the ring and can produce unrealistic sextupole gradients (black line in Fig. 9) If two spectral lines are taken into account the correction can have beneficial effects on the performance of the ring and an improvement of the Touschek lifetime of 10% was measured.

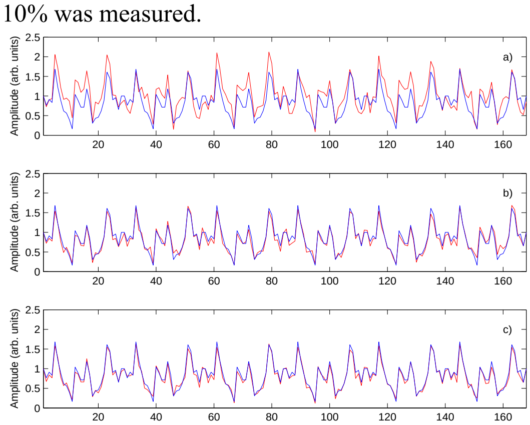

Fig. 7: Measurement and correction of the spectral line $Q_x - Q_y$ measured in the vertical plane: red – measured, blue - model, before correction (top) after one iteration (middle) after two iterations (bottom).

This technique has some limits: firstly it is based on the assumption that the first order perturbative theory adequately describes the nonlinear beam dynamics, secondly it relies on very precise measurements of the turn-by-turn data. Decoherence of the excited oscillations reduces the number of turns available and the machine tune stability has also to be controlled carefully if meaningful results are to be extracted. Nevertheless the indication provided by the experiment shows that this technique holds great potential for the characterisation of the nonlinear beam dynamics in storage rings.

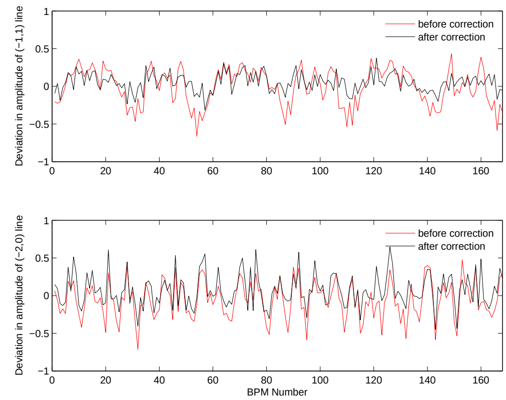

Fig. 8: Measurement and correction of the spectral line $Q_x - Q_y$ measured in the vertical plane (top) and of the $-2Q_x$ measured in the horizontal plane (bottom). Before correction (red), after correction (black).

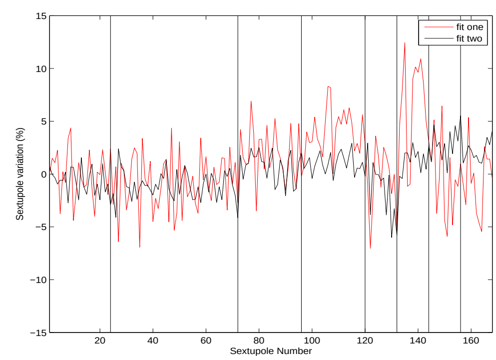

Fig. 9: Sextupoles gradient variation required by the fit procedure outlined in the text; black for the case where one resonance was targeted; red for the case where two resonances were targeted.

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