ONLINE SUPPRESSION OF THE SEXTUPOLE RESONANCE DRIVING TERMS IN THE DIAMOND STORAGE RING

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Abstract

Suppression of the sextupole resonance driving terms (RDTs) is a widely used technique for optimising the theoretical on and off-momentum dynamic aperture for electron storage rings. Recently, this technique was applied online to the Diamond storage ring, with suppression of individual RDTs achieved via a sextupole family to RDT response matrix [1]. In this paper we present recent studies of the method, in which the ability to improve the lifetime and injection efficiency are investigated. An extension of the technique is explored by combining it with the Robust Conjugate Direction Search (RCDS) optimisation algorithm [2].

INTRODUCTION

During the design stage for electron storage rings, great care is taken over the optimisation of the sextupole strengths in order to maximise the dynamic aperture. However, in the real machine this tuning can be spoilt by the presence of field and alignment errors, degrading the lifetime and injection efficiency. In order to combat this, many techniques have been developed in recent years that can be used to characterise and correct the nonlinear beam dynamics (see for example [3–6]). The topic is also of renewed interest at Diamond due to the forthcoming DDBA lattice modification [7], where it is anticipated the loss of symmetry will lead to an appreciable drop in both lifetime and injection efficiency.

One such correction method is described in [1]. In this, a sextupole family to resonance driving term (RDT) response matrix is constructed using the accelerator model, which can then be used to alter the RDTs directly on the machine. One of the strengths of this method is its apparent simplicity, making it straightforward to implement and robust in its application. In addition, since the individual RDTs are being directly controlled, lattice optimisation can be carried out at fixed chromaticity, a parameter whose value is often limited by other operational constraints.

In this paper we describe recent studies of the technique on the two double mini-beta lattice at Diamond [8]. The method used to correct the RDTs is first described, and online validation tests confirming the correct implementation of the techinique are presented. We conclude by presenting the results of tests combining the RDT correction with the Robust Conjugate Direction Search (RCDS) algorithm [2], in which the Touschek lifetime is optimised directly.

METHOD

The RDT correction method described in [1] is based around the identification of a set of “smart-knob” sextupole families, that is, combinations of sextupoles which will only adjust a single RDT when varied together. For the basic Diamond lattice, this requires the standard 8 sextupole families to be split into 24 [1]. This not only provides an under-constrained response matrix (RM) for the 18 first-order sextupole RDTs, but with an appropriate choice of families also breaks the symmetry of the ring such that both the real and imaginary driving terms can be adjusted.

Table 1: RDT Effects on Beam Dynamics

RDT	Effect
h_{11001}, h_{00111}	linear chromaticity in x and y
h_{20001}	synchro-betatron resonances
h_{00201}	dependance of $\beta_{x,y}$ on δp/p
h_{10002}	second-order dispersion
h_{21000}, h_{10110}	drives ν_x resonance
h_{30000}	drives $3\nu_x$ resonance
h_{10200}	drives $\nu_x + 2\nu_y$ resonance
h_{10020}	drives $\nu_x - 2\nu_y$ resonance

Sextupole RDTs

The contributions to the RDTs arising from the sextupoles can be calculated using [9]:

$$h_{jklmp} \propto \sum_{n=1}^{N_{sext}} (b_3 l)_n \beta_{xn}^{(j+k)/2} \beta_{yn}^{(l+m)/2} \eta_{xn}^{p} \times e^{i\{(j-k)\mu_{xn}+(l-m)\mu_{yn}\}} \tag{1}$$

where j,k,l,m and p are integers, $b_3 l$ is the integrated sextupole strength, $\beta_{x,y}$ and η_x are the usual Twiss parameters and dispersion function and $\mu_{x,y}$ are the horizontal and vertical phase advance. The impact of the first-order driving terms on the beam dynamics are summarised in Table 1.

Sextupole/RDT Response Matrix

The sextupole to RDT response is linearised by calculating the Jacobian of the system, namely:

$$\overline{\Delta h} = \frac{\partial \overline{h}}{\partial \overline{b_3}} \overline{\Delta b_3} \equiv S \overline{\Delta b_3} \tag{2}$$

where $\overline{h}$ is a vector containing the 18 real and imaginary sextupole RDTs and $\overline{b_3}$ is a vector containing the strengths of the sextupole families. To find the sextupole strengths required to implement a given change to the RDTs, the response matrix S can be inverted using e.g. Singular Value Decomposition and setting:

$$\overline{\Delta b_3} = S^{-1} \overline{\Delta h} \tag{3}$$

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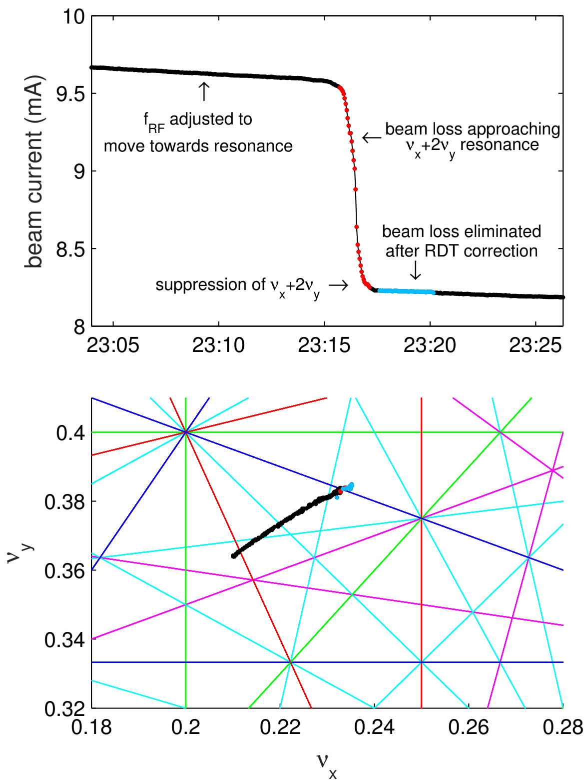

Figure 1: Suppression of the $\nu_x + 2\nu_y = 54$ RDT (see text for further explanation). Top: beam current as a function of time. Bottom: measured tune during the optimisation.

Implementation

For the present tests, calculations of the RDTs have been made using Accelerator Toolbox [10], and adjustment of the sextupole strengths is carried out using Middlelayer [11]. This decision allows the response matrix S to be calculated for different storage ring layouts and optics solutions automatically, and makes the development of a new graphical user interface (GUI) in Matlab straightforward.

CONTROL OF INDIVIDUAL RESONANCES

The method was first tested by investigating how well individual RDTs can be controlled. In this case, the most straightforward ones to manipulate are h_{11001} and h_{00111} (the horizontal and vertical chromaticities). Repeated tests moving these up and down individually and in combination were successful.

Following this, suppression of h_{10200} was investigated. This RDT excites the $\nu_x + 2\nu_y = 54$ resonance, which can easily be reached from the nominal Diamond working point (27.210, 13.364) by altering the RF frequency to shift the beam energy in a positive direction. This was carried out with chromaticity $\xi_x = 2$, $\xi_y = 2$. During this test, the linear optics and betatron coupling were first corrected using a parallelised version of LOCO [12], and all IDs were fully open. The electron beam was kicked at 5 Hz with a single turn 'pinger' magnet to an amplitude of 1 mm in each plane to enable the turn-by-turn BPM spectrum to be acquired.

The results of the tests are shown in Fig. 1. Initially, the beam current shows only a gradual decay over time (black dots). The beam losses increase sharply as the tune approaches the resonance (red dots), at which point $Re[h_{10200}]$ and $Im[h_{10200}]$ are adjusted so as to suppress the losses completely (blue dots). After this, the tune is returned to the nominal working point. Complete suppression of the beam losses was achieved by a correction of $\Delta Re[h_{10200}] = -1.41$ and $\Delta Im[h_{10200}] = -0.90$, corresponding to a maximum change in sextupole strength of $< 0.9\%$.

For negative momentum deviations, the next dominant resonance is found to be $3\nu_y = 40$. This resonance is excited by skew-sextupole fields, for which there are no suitable trim magnets in the Diamond storage ring. By introducing finite betatron coupling back into the ring, it should in theory be possible to influence its amplitude using h_{30000}. When attempting this online, it was found that whilst it was possible to reduce the rate of beam loss when approaching the resonance, this did not translate into an improvement in the Touschek lifetime.

OPTIMISATION USING THE RCDS ALGORITHM

RCDS Algorithm

Given the large number of RDTs available for adjustment, here we investigate whether an effective correction can be achieved by allowing the RCDS optimisation algorithm [2] to control them directly. This algorithm was developed specifically for tasks involving optimising against observable parameters which are subject to a significant amount of noise. The method uses a conjugate direction search following Powell's method to determine the optimum direction in which to vary the input parameters, and accounts for the random noise on the measurement by bracketing the response around the minimum and using a parabolic fit to the data. It has been successfully applied at a number of other facilities with impressive results (see for example [13–15]).

Lifetime Studies

Measurements of beam lifetime can typically take several minutes before giving reliable readings, and as such are not ideally suited for use in optimisation algorithms. In these studies we used a photomultiplier tube (PMT) with a fast scintillator and counter installed downstream of the collimators as a suitable proxy. This has been found to provide an accurate indication to any change in lifetime within a few seconds in response to a change in any given RDT.

First tests of the algorithm again concentrated on driving a single RDT (both real and imaginary components). This was done with the betatron coupling corrected and with moderate stored bunch charge in order to enhance the Touschek losses. Fast orbit, RF frequency and tune feedbacks were all enabled in order to minimise unwanted second order effects which may impact the lifetime.

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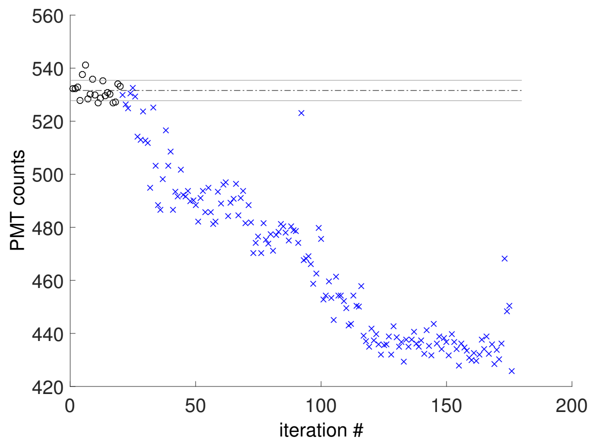

Figure 2: Evolution of PMT losses over a single cycle of the RCDS algorithm (see text for further explanation).

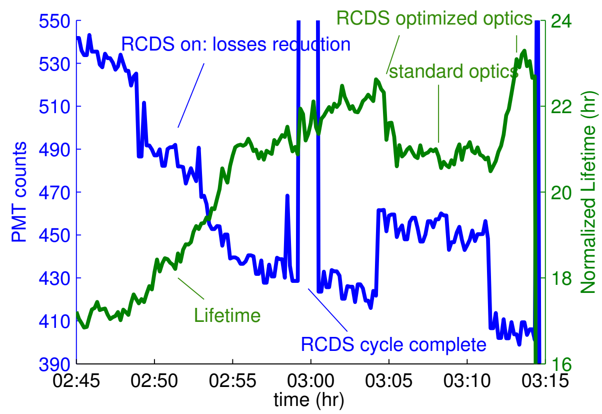

Figure 3: Change in normalised lifetime and loss-rate as a function of RCDS iteration number. The effect of switching between initial and optimised sextupoles is highlighted.

These initial tests highlighted a number of issues. Firstly, despite the fact that h_{11001} and h_{00111} were left fixed, hysteresis built up during the optimisation caused significant change to the chromaticity. This could be cleared by cycling the magnets, but did lead to a change in lifetime which could not be attributed to the change in RDTs. To minimise the impact of this, it was important to establish suitable bounds within which the RDTs could be varied. Another effect caused by the variation in sextupoles was that the coupling was also altered due to the feed-down effect of vertical beam displacement within the magnets. This again caused variation in lifetime unrelated to the RDTs. To counter this, the vertical emittance feedback was also enabled during later runs. A final point to note was the impact of electron polarisation. This causes the lifetime to grow over the first 90 minutes following injection [16], again giving a misleading impression for the optimisation.

Having studied the RDTs in turn, the algorithm was executed on all RDTs simultaneously (bar h_{11001}, h_{00111} and h_{10002}). The evolution of the PMT losses during the optimisation are shown in Fig. 2. In this, the first 20 iterations

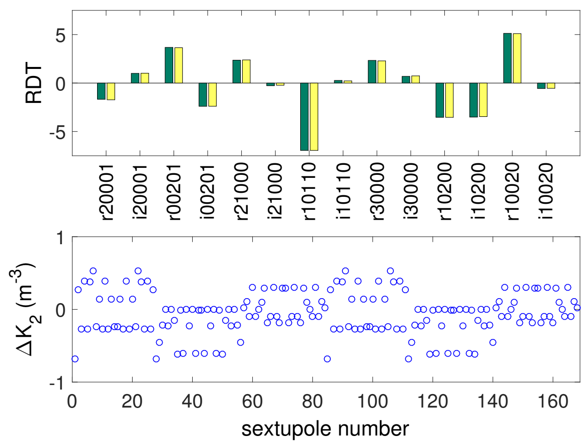

Figure 4: Top: RDTs before (green) and after (yellow) optimisation. Bottom: Associated change in sextupole strength.

(highlighted as black circles) are used to quantify the level of noise in the measurements (horizontal band), following which the optimisation is begun (blue crosses). As can be seen, the algorithm was able to produce a significant drop in the measured loss-rate within 150 cycles (about 10-15 minutes to complete).

To confirm that the optimisation was indeed having the desired effect on the beam lifetime, the sextupole settings were reverted to the initial values and back again (see Fig. 3). The result of the optimisation was found to be an increase of ~1 h in lifetime (after correcting for a minor variation in ϵ_y). In Fig. 4 the RDT amplitude before and after the optimisation, along with the required change in sextupole strength are shown. These data emphasise the fact that only minor changes to the sextupoles were required in order to maximise the beam lifetime.

Injection Studies

Preliminary tests have also been made to see if a similar approach can be used to maximise the injection efficiency. In this case the algorithm was unsuccessful, thought to be due to the lack of an effective handle on the resonances which are known to limit the injection process. Further studies are required to confirm this theory.

CONCLUSION

The RCDS algorithm has been used to optimise the RDTs in the Diamond storage ring directly. Whilst this gave a clear improvement in lifetime, the benefit was found to be relatively small in absolute terms due to the presence of a strong skew-sextupole resonance. The high-level software tools to control the RDTs are now integrated into the existing Middlelayer and Accelerator Toolbox infrastructure at Diamond, and are expected to be a valuable additional tool for commissioning the DDBA cell later this year.

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