

# ACTIVE OPTICS STABILISATION MEASURES AT THE DIAMOND STORAGE RING

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## Abstract

The Diamond storage ring is currently operated with 26 insertion devices (IDs), including 14 in-vacuum IDs, 7 APPLE-II type helical undulators and 2 superconducting wigglers. Differences in the design, construction and operation of these devices, combined with different Twiss parameters at the source point, mean each has a different impact on tune stability and beta-beat. In turn, these parameters affect the on and off-momentum dynamic aperture and ultimately impact on the injection efficiency and lifetime. Another source of optics variation arises from the coherent tune shift with current, which when injecting from zero current causes the tune to span the available good-tune region. In this paper we discuss the difficulties of operating the Diamond storage ring in top-up mode with these effects, and present the various measures taken to stabilise the storage ring optics.

## INTRODUCTION

One of the key challenges for modern 3rd generation light sources is to be able to maintain stable, predictable conditions for time-scales ranging from fractions of a second up to many days or even weeks at a time. For machines operating in top-up mode, the impact of insertion devices (IDs) on operational performance is of particular concern, as these are typically the primary source of short-term optics perturbations and can lead to large variations in injection efficiency or lifetime, requiring more frequent injection cycles and result in a prolonged disturbance to the stored beam. Longer term, other effects such as physical movement of the magnets, drift in BPM electronics or power supply variations can also lead to changes in the optics that must be corrected.

To combat the influence that particular IDs may have on storage ring performance, feed-forward schemes are generally applied. At Diamond, this typically means local trim dipole magnets to correct for orbit distortions; however, several devices also require compensation for the induced tune-shifts and beta-beat.

This paper begins by describing the requirements placed on tune stability to maintain high injection efficiency, before presenting the measures taken to stabilise the storage ring linear optics. An overview of the different feed-forward schemes that have been implemented is given, and the performance of a tune feedback application is described. Measures taken to stabilise the vertical emittance can be found in a previous report [1].

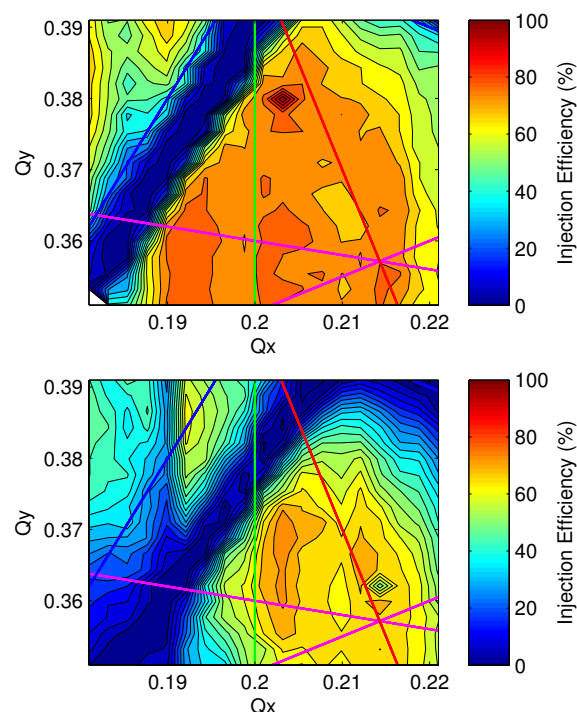


Figure 1: Injection efficiency vs. tune. Top: I05 open. Bottom: I05 at 25 mm, V-polarisation, active shims enabled.

## GOOD TUNE REGION

As the number of IDs installed in the Diamond storage ring has gone up, injection efficiency has become increasingly sensitive to the tune point. The ID with greatest impact on injection efficiency is I05, a 4.96 m long, APPLE-II type helical undulator [2] (see Fig. 1). In the upper plot of Fig. 1, injection efficiency as a function of tune is shown for I05 open to 150 mm, with the remaining IDs closed to typical values. In this case, a wide region of tune-space exists in which the injection efficiency is  $>80\%$ . Despite the fact that a strong sextupolar resonance ( $2Q_x - Q_y$ ) limits the efficiency for some tune values, it is usually sufficient simply to operate far from this region.

In the lower plot, I05 was closed to 25 mm gap (vertical polarisation). This has the effect of not only shrinking and lowering the maximum injection efficiency, but also altering the tune-shift with amplitude such that the tunes at which the off-axis injected beam is influenced by the sextupole resonance are shifted. These two observations indicate a need for tighter control of the operating tune point.

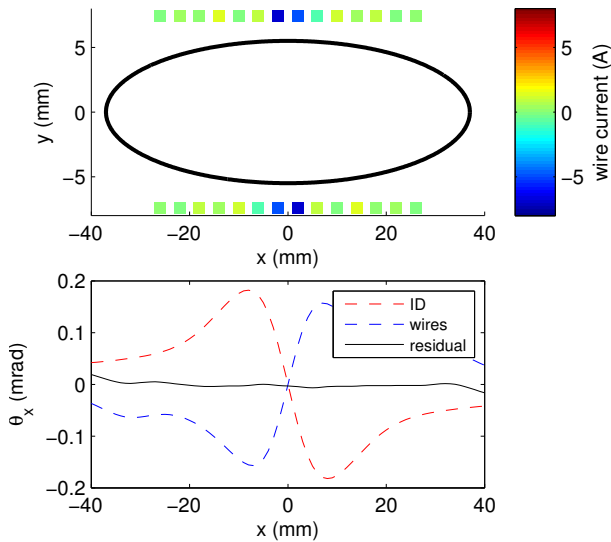


Figure 2: Top: wire currents to compensate for I05 in circular polarisation mode. Bottom: horizontal kick due to ID (red), shim wires (blue) and residual kick experienced by the beam (black).

## TUNE FEED-FORWARD SCHEMES

The linear optics are routinely corrected during start-up using the LOCO application [3]. This is done with IDs closed to typical gaps and, assuming a well-optimised injector, results in an injection efficiency >90 % and a lifetime of >15 h at 300 mA (900-bunch fill pattern). For the majority of IDs, this correction is all that is required to ensure good performance for the run period of typically 6-8 weeks; however, several devices additionally require an active correction for gap and/or phase changes.

### I12 and I15

The Diamond storage ring contains two high-field superconducting wigglers, each of which induce a large tune shift and significant beta-beat [4]. To correct for this, a combination of alpha-matching [5] using the quadrupole triplets either side of the IDs, plus a global tune correction using two families of quadrupoles in the long straights, is applied. The quadrupole triplets are also used to control dispersion in the straight in order to minimise the effect the IDs have on the emittance. A detailed description of the performance of this scheme can be found in [4].

### I05

The I05 APPLE-II undulator has a larger impact on the electron beam dynamics than other IDs due to its relatively long length and large beta functions at the centre of the straight ( $\beta_x^* = 9.75$  m,  $\beta_y^* = 5.88$  m). During the design stage it was identified that this would lead to significant linear and nonlinear optics distortions, particularly in vertical polarisation mode [2].

To combat these effects, active shim wires running parallel to the device have been installed on the vacuum chamber,

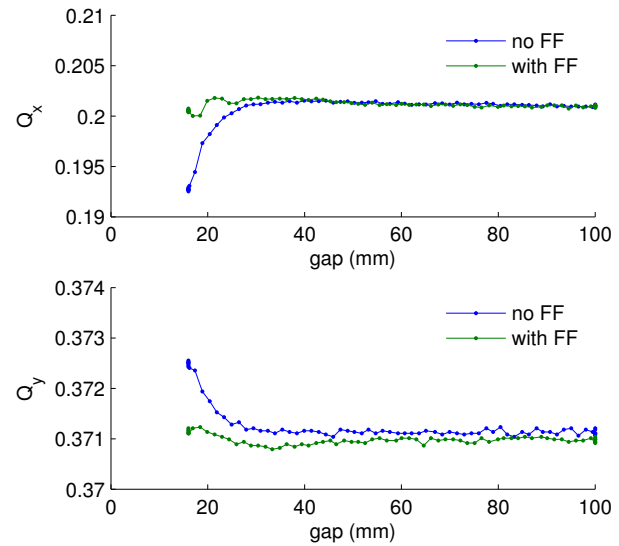


Figure 3: Tune shift with gap for J09 (vertical polarisation).

similar to those used at BESSY-II [6]. In this scheme, the current flowing through the wires is adjusted such that a magnetic field that gives an equal and opposite kick to the beam is generated, thus suppressing the dynamic multipoles from the ID. This is illustrated in Fig. 2, where the kick due to the ID, the effect of the shim wires and the residual kick experienced by the beam are all shown.

Following installation of the device, experimental tests demonstrated that, for vertical polarisation mode, the active shim wires were able to reduce the residual beta beat from above 30% to below 5% in both planes, with the tune shift reduced from  $[-0.036, 0.025]$  to  $[0.004, 0.001]$  in  $[x, y]$  respectively. Despite this reduction, when operated in combination with the other IDs in the ring, the residual tune shifts are still large enough to move the working point close to the region of low injection efficiency shown in Fig. 1. To counter this, the nominal tune point has recently been moved from  $[27.201, 13.371]$  to  $[27.204, 13.365]$ .

### J09

The final device requiring feed-forward compensation is the J09 APPLE-II undulator, which is located in a mini-beta section where  $\beta_y$  is low (1.5 m) but  $\beta_x$  is large (24.9 m) [7]. As such, the device has very low impact in horizontal polarisation mode, but leads to significant tune-shift and beta beat in vertical or circular polarisation.

Since the undulator can be operated with arbitrary gap and phase, 2D quadrupole feed-forward tables are now required. Alpha matching is performed using quadrupole doublets either side of the ID, and a global tune correction is again carried out using doublets in the long straights. Explicit control of the dispersion was found not to be necessary in this case. As with I05, I12 and I15, the feed-forward tables were constructed from the machine model using an ideal kick-map representation of the ID [8]. The resulting tune-shifts with gap for J09 are shown in Fig. 3.

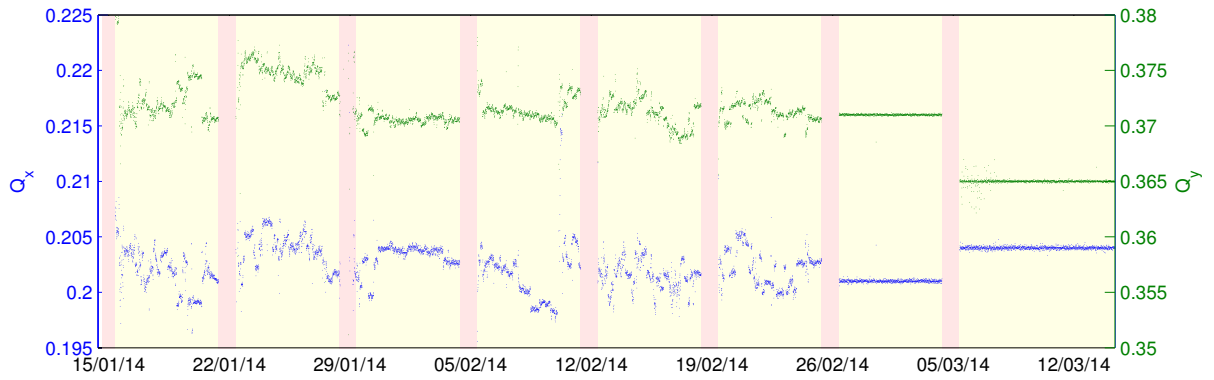


Figure 4: Measured tunes during Run 1-2014, including 6 weeks of operation with TFB off and 2 weeks with TFB on. A change in nominal tune point was carried out on 05/03/2014. Machine development days are highlighted in red.

## TUNE FEEDBACK

Whilst the above feed-forward schemes are able to suppress the majority of the ID-related optics distortions, there is still a residual tune variation which must be corrected if predictable storage ring conditions are to be maintained. This is achieved using a Python-based tune feedback (TFB) application, more details of which can be found in a companion paper [9].

### Feedback Implementation

The TFB uses a model response matrix  $\mathbf{R}$  to calculate the required change in quadrupole currents  $\Delta\mathbf{I}$  for a given tune error  $\Delta\mathbf{Q}$ , where

$$\Delta\mathbf{Q} = \mathbf{R}\Delta\mathbf{I} \quad (1)$$

The response matrix is constructed using the quadrupole triplets either side of the insertion straights, giving a total of 144 quadrupoles out of a possible 248. The feedback runs at 1 Hz, and at each iteration  $n$  performs the calculation

$$\begin{aligned} \Delta\mathbf{Q} &= \mathbf{Q}_{meas}(n) - \mathbf{Q}_0 \\ \mathbf{Q}_{int}(n) &= \mathbf{Q}_{int}(n-1) + f\Delta\mathbf{Q} \\ \mathbf{I}_{FB}(n) &= -\mathbf{R}^{-1}\mathbf{Q}_{int}(n) \\ \mathbf{I}_{tot}(gap, n) &= \mathbf{I}_{set} + \mathbf{I}_{FF}(gap) + \mathbf{I}_{FB}(n) \end{aligned} \quad (2)$$

where  $\mathbf{Q}_{int}$  is the integrated tune correction,  $\mathbf{Q}_{meas}$  is the measured tune vector and  $\mathbf{Q}_0$  is the target tune. At each iteration, only a fraction  $f$  of the calculated value is applied. The correction  $\mathbf{I}_{FB}$  is held separately to the magnet setpoints  $\mathbf{I}_{set}$ , such that the final output current for a given quadrupole power supply  $\mathbf{I}_{tot}$  is the sum of  $\mathbf{I}_{set}$ ,  $\mathbf{I}_{FB}$  and  $\mathbf{I}_{FF}$ . In the majority of cases, the contribution from ID feed-forward schemes  $\mathbf{I}_{FF}$  is zero.

The integrity of the data is checked by the feedback before corrections are applied. These checks include ensuring that the measured tune value is valid, fresh and lies within an absolute tolerance window of  $\mathbf{Q}_0$ , that the step-change in  $\mathbf{I}_{FB}$  is below 0.01 A, and that the accumulated value is below 0.1 A for each quadrupole. The TFB can also be used

interactively to apply a single correction (for which some of these checks are bypassed), or run in looped mode during injection.

The TFB stores the integrated tune error rather than integrated quadrupole correction as this makes it more stable to noise. It is also a more intuitive parameter to consider when monitoring the effect of the feedback over time, and allows a correlation of the response of feedback events such as ID gap changes or injection cycles to be made.

### Operational Performance

The TFB has been in use since the final 2 weeks of Run 1 in 2014 (see Fig. 4). A conservative value of  $f = 0.2$  is currently in use. This allows a stable operation of the feedback, with transient tune shifts due to ID gap changes corrected within a few seconds. Over a typical 10 minute period, the tunes are stabilised to the level  $1 \times 10^{-4}$  and the standard deviation in quadrupole currents is  $\sim 0.3$  mA.

## CONCLUSIONS

Using a combination of local feed-forward schemes for optics correction and a global tune feedback, the impact of ID gap and phase changes has been significantly reduced. The betatron tunes are held at nominal within the precision of the measurement, leading to a much greater predictability in injection efficiency and stored beam lifetime.

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