ELECTRON BEAM COMMISSIONING OF THE DDBA MODIFICATION TO THE DIAMOND STORAGE RING

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Abstract

The Diamond storage ring has been modified by replacing one of the existing double bend achromat (DBA) cells with a double-DBA (DDBA) cell [1]. This change represents the largest modification to the storage ring since it was first commissioned in 2006, and was installed and fully commissioned during an 8 week shutdown in autumn 2016. In view of this tight schedule, the planned commissioning steps and all high-level software needed to be developed and tested in advance. Electron beam commissioning occupied the final 2 weeks of the shutdown, during which the injected electrons were captured and accumulated, the correct linear lattice was established, the nonlinear beam dynamics were studied, IDs were closed and the target 300 mA was achieved. This paper presents an overview of these activities.

INTRODUCTION

The replacement of a single DBA cell in the Diamond storage ring with a DDBA structure was completed in autumn 2016, thereby creating space for an additional insertion device (ID) in the centre of the arc [1, 2]. In order to minimise disruption to users, electron beam commissioning was restricted to a 2 week period at the end of the shutdown, and the target user-relevant parameters were left unchanged after the modification.

PREPARATION FOR COMMISSIONING

High-Level Software

Although the majority of operational tools are implemented as Python applications, prototyping and development work is typically carried out using Matlab Middle Layer (MML) [3]. To this end, a new storage ring instance was created that incorporates the changes to the ring, and new golden response matrices for orbit, tune, chromaticity and vertical emittance control were generated using this.

Several developments were necessary for the high-level applications [4]. For the fast orbit, slow orbit and RF feedbacks, the only changes to the code were those needed to account for the additional BPMs and correctors in the DDBA cell, plus application-specific enabling/disabling of actuators and monitors. For the tune feedback [5], the decision was taken to use only the quadrupole triplets in DBA cells, reducing the number of active quadrupoles from 144 to 138. This solution gave the best compromise in terms of keeping quadrupole gradient changes small whilst minimising the impact on emittance, beta-beat and chromaticity.

Changes to the vertical emittance feedback [6] were more substantial. In this case, the original method of controlling the vertical emittance by adding a single offset to all skew-quadrupoles was found to be unacceptable due to an increase in betatron coupling. This led to large beam-tilt and poor control of the true eigen-emittance. As such, a new method was developed based on a vector of skew-quadrupole changes that primarily drives only the vertical dispersion.

Lastly, a number of new Matlab-based tools were developed to support commissioning, such as visualisation of first-turn trajectory (after correcting for BPM nonlinearities) and beam survival around the ring using BPM intensities.

Machine Tests

Each stage of the electron beam commissioning procedure was tested ahead of installation. These studies included work to characterise the injection process [7], confirmation that the injector and diagnostics function correctly at the new RF frequency [8], moving the septum closer to the stored beam to allow on-axis injection and testing the commissioning procedure using the pre-existing cell 2 DBA magnets.

FIRST STORED BEAM

First turns in the modified storage ring were achieved on-axis, with the non-DDBA magnets left in their original state and the DDBA magnets set to their model values scaled to 3.015 GeV. This configuration allowed 4 to 5 turns to be achieved, increasing to around 150 turns after adjusting the correctors in the DDBA cell. The injected beam trajectory for this is shown in Fig. 1, where the impact on phase advance from the adjustment can clearly be seen. The final
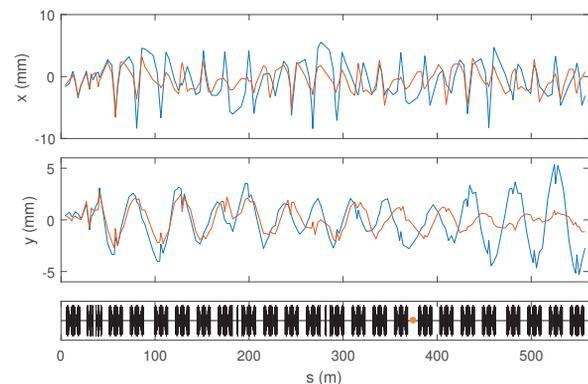

Figure 1: First-turn trajectory for the injected beam before (blue) and after (red) adjustment of the DDBA steerers.

corrector values were set to maximise survival time rather than to minimise trajectory errors.

Following this, the non-DDBA magnets were changed to their new nominal values. This did not cause any significant change in either the trajectory or survival time, allowing the RF cavities to be powered up. This enabled the injected beam to survive until the next injection cycle, making it possible to capture beam on a single shot. A first tune measurement at this stage gave Q_x/Q_y=.136/.283, compared to model values of .184/.284.

The next step was to switch to off-axis injection and accumulate beam. This proved to be straightforward, with injection efficiency improving after a combination of closed orbit and tune corrections. The initial target of 10 mA was achieved within 3 hours of first capturing beam, pausing at 0.5 mA, 1 mA, 2 mA, 5 mA and 7 mA to allow the vacuum to recover and to monitor temperatures. Once at 10 mA, the H/V chromaticity was stepped from 0.8/1.2 to 1.3/1.7 (compared to model values of 2.1/1.0). This gave a further increase in injection efficiency from 10% to 40%.

MACHINE CHARACTERISATION

Initial Checks

Preliminary optics studies began with polarity tests for all corrector, quadrupole and sextupole magnets by comparing the machine response to that anticipated from the model. From this, it could also be established that the machine was operating at the correct integer tune. The high-level feedback applications were tested with no issues found, and aperture scans using orbit bumps did not identify any obstructions.

Following on from this, the time-constant for step-changes to the new, solid-yoke quadrupole magnets was measured. This highlighted an increase in settling time compared to the original, laminated magnets, which needed to be taken into account in the beam-based alignment (BBA) routine.

After an initial BBA of all new BPMs, attempts to correct the orbit to zero using all singular values were unsuccessful due to a horizontal corrector magnet (HCM) saturating. It was noted that all HCMs were negative, indicating insufficient bend from the main gradient dipoles. After increasing all dipoles by 0.65%, the orbit could be fully corrected.

Linear Optics Correction

The first attempt to correct the linear optics using a modified version of LOCO [9] indicated the gradients of the dipoles were still too low by 0.5-1%. After applying these corrections plus two further iterations, it was possible to bring the measured beta-beat down from an initial ±50%/25% in H/V to below 5% in both planes, and the injection efficiency increased to 80%.

The corrections to the dipole strengths were however insufficient to completely remove the negative bias of the HCMs in the DDBA cell. In order to remove this bias, a model-based response matrix was used to calculate the best realignment for each dipole keeping the gradients fixed. These corrections were applied in two stages, firstly correcting the

alignment of dipole 3, then dipoles 1 and 2. The final adjustments in position and gradient for each of the 4 dipoles in the DDBA cell are given in Table 1.

Table 1: Gradient Bend Adjustment

Magnet	Displacement (mm)	ΔK (%)
Dipole 1	+0.7	+1.93
Dipole 2	+0.5	+1.47
Dipole 3	+0.8	+0.81
Dipole 4	+0.0	+2.09

Tune Scans

The sensitivity to betatron tune was investigated with and without IDs closed. In order to reduce the measurement time, lifetime was assessed by counting losses with a scintillation screen and photomultiplier tube located behind the collimators. This demonstrated the lifetime is only weakly dependent on tune point (for fixed vertical emittance).

The injection efficiency showed greater sensitivity, particularly with IDs closed (as shown in Fig. 2). In this case, many broad resonances were visible, with no injection possible at some values. These studies prompted a change in nominal tune point from .184/.284 to .172/.273.
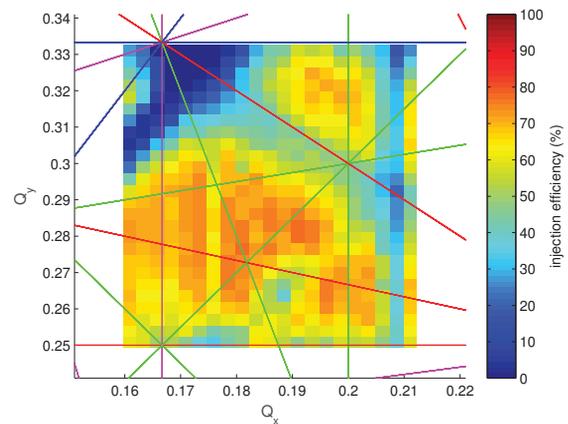

Figure 2: Injection efficiency vs. tune point with IDs closed.

Impact of IDs

After the change in nominal tune point, closing the IDs did not lead to a substantial change in machine performance. Beta-beating initially increased to 15-20% and injection efficiency dropped by ~10%, but these could be recovered with chromaticity and LOCO corrections. Orbit distortions due to gap changes remained at the 5-10 μm level. However, energising the superconducting wigglers was found to cause the emittance to increase from 2.7 to 3.2 nm.rad due to the larger $\mathcal{H}$-function at their locations. A new optics solution with lower $\mathcal{H}$-function in straight 12 is now under development, for which the emittance remains constant with wiggler field.
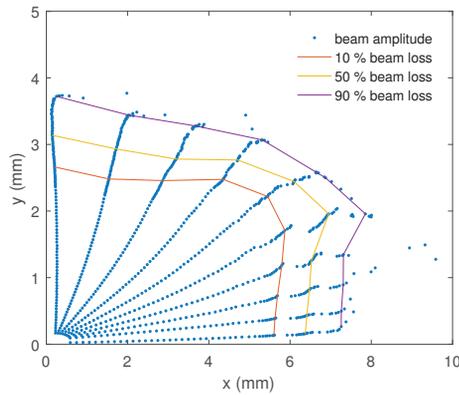
Figure 3: Dynamic aperture at the injection point following the installation of the DDBA cell.

Figure 4: Lifetime vs. RF voltage.

Dynamic Aperture

The dynamic aperture (DA) measured for the bare lattice (IDs open) is shown in Fig. 3. This was measured by kicking the beam using a single-turn pinger magnet, recording and processing the raw turn-by-turn BPM button data using the method described in [10], and translating the amplitudes back to the injection point using the model. In the figure, boundaries showing 10% beam loss (red), 50% beam loss (orange) and 90% beam loss (purple) have been highlighted.

The measured horizontal DA following the installation of the DDBA cell is substantially reduced compared to the pre-DDBA lattice. Before installation, amplitudes above 12 mm could be measured routinely [10], compared to 6-8 mm now. This reduction is reflected in the injection efficiency, which has dropped from 85-90% to 75-80% for the bare lattice. The measured DA in the vertical plane has been largely unaffected by the new cell.

Lifetime

Lifetime as a function of RF voltage with and without IDs is shown in Fig. 4. For the bare lattice, a comparison is also given to the Touschek lifetime computed using the Brück formula [11], for which the momentum acceptance is assumed to be limited purely by the RF aperture, and was scaled to match the measured lifetime. At low voltages there is excellent agreement between the curves. Above ~1.6 MV the curves begin to diverge, indicating the point where the lattice momentum acceptance begins to take over from the RF. This corresponds to a momentum acceptance of +2.1% / -2.5%, in good agreement with complementary measurements taken by shifting the RF frequency and noting the first point of beam-loss. With IDs closed the peak lifetime shifts to 2.6 MV due to the increased energy spread, bunch length and change in energy loss per turn.

Figure 5 shows the stored current and lifetime normalised to 300 mA, $\epsilon_y = 8$ pm.rad and 900 bunches for the period immediately before and after the installation. During the initial beam-commissioning period the gas lifetime was dominant, after which the Touschek component took over (~70
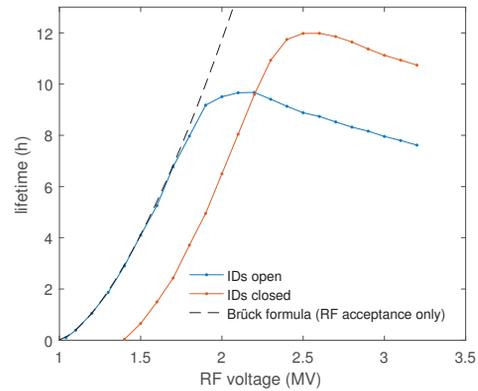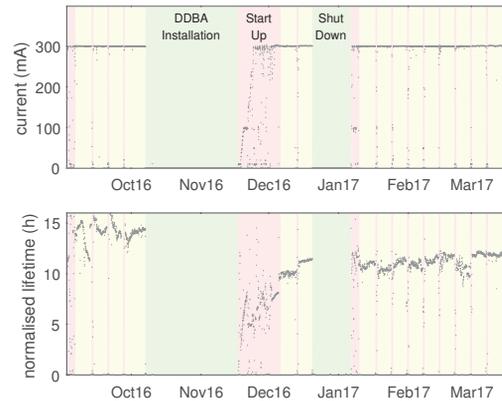

Figure 5: Stored beam current (top) and normalised lifetime (bottom) over the commissioning period. Shutdown periods are highlighted in green, machine development in red and user time is shown in yellow.

Ah accumulated dose [12]). Since then, the lifetime has been stable at ~12 h (compared to ~14 h before installation).

CONCLUSIONS

Commissioning of the DDBA cell has been a success, with 10 mA reached on the first day and 300 mA within one week. Beam was returned to users on schedule, with the vertical emittance initially set to 10 pm.rad due to lifetime constraints and vacuum-related instabilities. This was lowered to the standard 8 pm.rad in Jan 2017 once the vacuum had improved. Although the lifetime and injection efficiency have reduced by 10-15% compared to pre-DDBA values (in line with expectations), reliability has been excellent (MTBF was 312 h in Run 5 2016 and 155 h in Run 1 2017).

Characterisation of the machine performance is on-going. The primary focus is on understanding and optimising the non-linear beam dynamics, establishing the impact on collective effects [13] and implementing a low-alpha configuration [14]. Operation with different filling patterns (such as hybrid and 156 bunch modes) is being assessed, as is the impact on orbit stability [15] and stored beam energy.

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