STUDIES TO OPTIMIZE THE DIAMOND LIGHT SOURCE BOOSTER SYNCHROTRON AS A 100 MeV STORAGE RING

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Abstract

The Diamond Light Source injector consists of a 100 MeV Linac and 3 GeV booster synchrotron. These were commissioned in 2005 and 2006 respectively, and have provided acceptable performance as an injector since then. To advance a programme of work in evaluating and optimizing new control algorithms for orbit stability for Diamond it was decided to use the booster synchrotron as a test platform by operating it in DC mode at 100 MeV. In support of this work and to improve the operational performance of the booster a series of studies has been carried out to better understand and characterize it.

THE DIAMOND BOOSTER

The Diamond booster synchrotron is a missing dipole FODO lattice structure with a circumference of 158.4 m [1]. The booster lattice comprises 36 dipoles, two families of 22 quadrupoles, two families of 16 sextupoles and 22 correctors in each plane of motion. The booster is designed to operate at a repetition rate of 5 Hz. During each cycle, beam is injected on-axis from a 100 MeV linac, and dipoles and quadrupoles are ramped sinusoidally to accelerate the beam to 3 GeV before extraction and transport to the Diamond storage ring. Sextupole currents are changed during the ramp to correct for induced fields and the booster RF voltage is ramped as the beam energy increases [2,3]. The booster and linac are used to fill the storage ring from empty, and, since October 2008, Diamond has been operating in top-up mode, with the booster supplying beam to the storage ring every 10 minutes to maintain a constant storage ring current for users [4]. Vacuum pressure in the booster is maintained in the mid-10^{-10} mbar range without beam.

STORED BEAM IN THE BOOSTER

Initial efforts to store beam in the booster by simply turning off all magnet and RF ramps and maintaining 100 MeV injection optics resulted in a beam lifetime of less than one second, necessitating a “kick-out and replace” approach to maintain beam current. A better working point was established by scanning the currents in the two quadrupole families and measuring the beam current integrated over 200 ms with all other parameters kept constant. Results are shown in Figure 1, with red indicating high integrated current and blue low. The upper plot is integrated current against quadrupole currents and the lower plot is integrated current presented as a function of fractional tune measured by a stripline BPM. Decreasing tune with increasing quadrupole current indicated tunes above the half-integer.

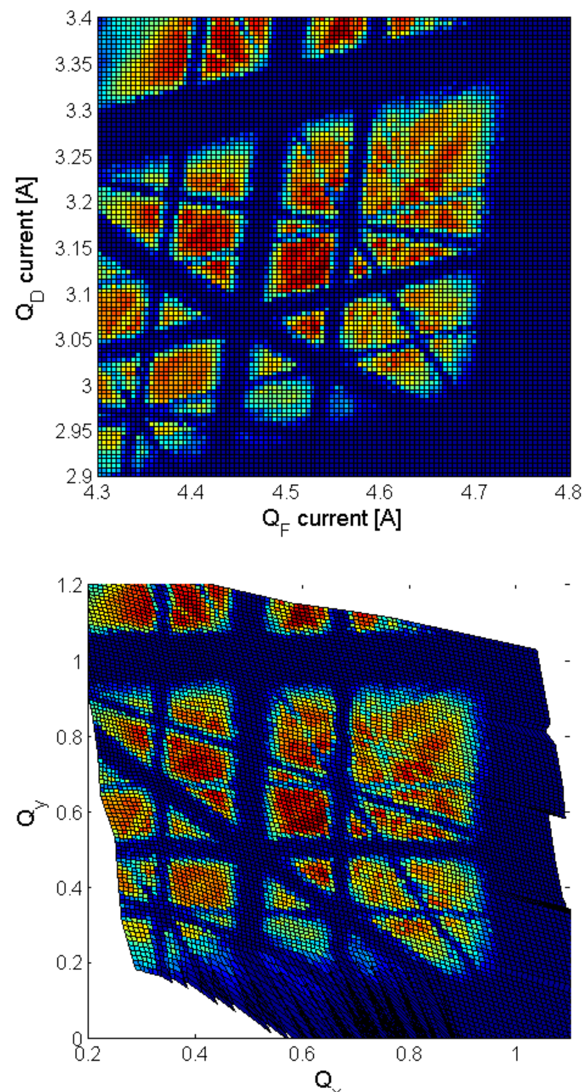

Figure 1: Integrated booster current as a function of quadrupole current (above) and betatron tune (below).

Betatron resonances up to third order are immediately obvious, as are multiple possible working points. One particularly attractive region is near $Q_x = 0.6$, $Q_y = 0.6$, although the $Q_x = Q_y$ resonance is present but faint and must be avoided. Optimisation of sextupole currents and injection magnets at this working point enabled beam to be stored in the booster with exponential decay lifetimes of several minutes. Figure 2 shows the decay of a train of 120 bunches stored in the booster. Similar currents are possible with single bunch operation, although initial tests indicate a much shorter lifetime.

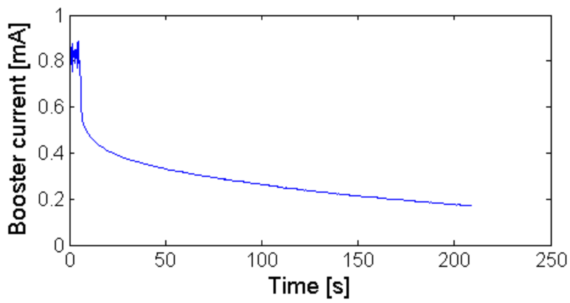

Figure 2: Decay of stored beam current.

Operating parameters for stored-beam mode are held in a back-up file and can be quickly restored for operation. Remnant field in the magnets is not completely cleared by a simple magnet current cycle and so some fine tuning based on tune measurements is necessary each time the booster is put into this mode. The dynamic range of the booster LLRF amplitude loop is also limited and so the RF must be operated in the clipped CW mode developed for cavity conditioning [5] in order to minimise synchrotron oscillations. Synchrotron frequency with minimum stable RF power to the cavity is typically 40 kHz, corresponding to 40 kV cavity voltage. Nevertheless, the switch from normal operating conditions to stable, long-lived stored beam in the booster can generally be completed within 15 minutes, allowing the booster to be used in this manner during interventions in the storage ring such as RF cavity conditioning or ID work during machine development periods.

STORED BEAM PARAMETERS

Booster magnet power supplies must operate in DC mode well below their average design currents to store beam at 100 MeV, but stability does not appear to be a problem. There is some small variation in tune with time but this is not sufficient to lose beam. Tunes for stored beam immediately following injection measured using turn-by-turn BPM data for beam with a stripline exciter are shown in Figure 3, giving fractional tunes and ranges of $Q_x = 0.435 \pm 0.05$ and $Q_y = 0.41 \pm 0.1$ (although the actual tune is above the half-integer).

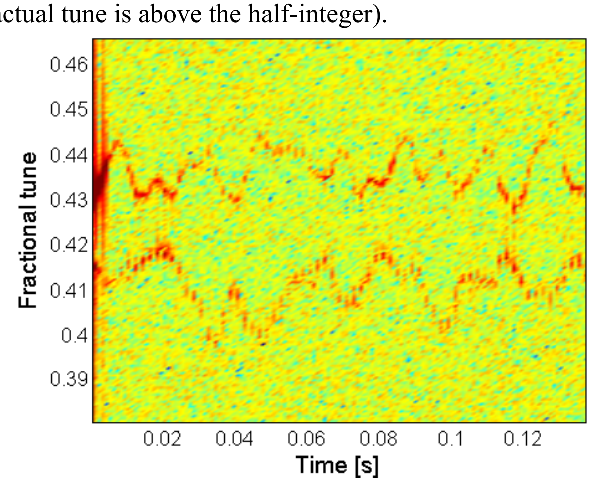

Figure 3: Stability of horizontal (upper) and vertical (lower) fractional tunes immediately following injection.

There is no direct measurement of emittance available for the booster, but the very long damping times at 100 MeV, compared with the 3 GeV values in Table 1, suggest that the stored beam emittance should only decay slowly from the linac value at 100 MeV. Linac emittance is routinely measured to be in the range 170 to 250 nm.rad depending on bunch charge and quality of linac tuning.

Beam emittance can be measured in the booster-to-storage ring (BTS) transfer line following extraction after 100 ms using a parametric scan of two quadrupoles combined with a profile measurement on an OTR screen. The effects of radiation damping in the horizontal and vertical planes and quantum excitation in the horizontal plane are clear in Figure 4. Unfortunately, the booster extraction magnet and BTS quadrupole supplies become unstable at low currents, and so a precise measurement of emittance at 100 MeV is not possible at the moment, but clearly the beam is far from its equilibrium state after this short time, consistent with the calculations in Table 1.

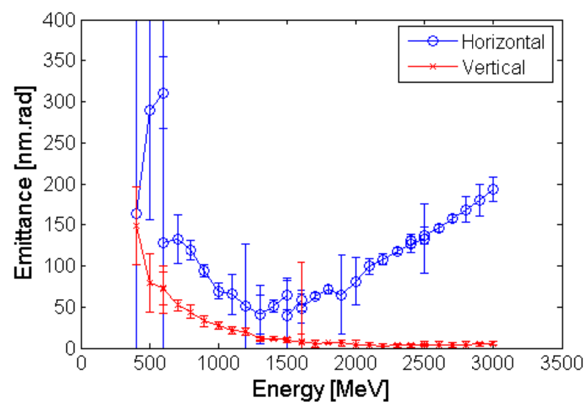

Figure 4: Transverse emittance of extracted beam.

Table 1: Transverse and Longitudinal Damping Times

Energy	τ_x	τ_y	τ_s
100 MeV	160 s	150 s	72 s
3 GeV	5.8 ms	5.5 ms	2.7 ms

BEAM-BASED ALIGNMENT

A programme of beam-based alignment (BBA) has begun in the booster in order to establish the electrical offset of the BPM centres from the magnetic centres of the adjacent quadrupoles. A modified version of the Accelerator Toolbox (AT) Middlelayer routine “quadcenter” was used for this task [6]. Diamond booster quadrupoles do not have individual power supplies, and so a separate power supply was added across the terminals of each of the quadrupoles in turn and incorporated into the control system for BBA measurement and analysis. The booster BBA can only be carried out during a machine shutdown because of the requirement for regular access to the vault to change the physical connections of the auxiliary power supply.

Results from the first round of the BBA are shown in Figure 5. Offsets are comparable with those measured in the initial BBA of the Diamond storage ring [7]. It is planned to apply the BBA offsets to the BPMs and to complete the correction in a future shutdown.

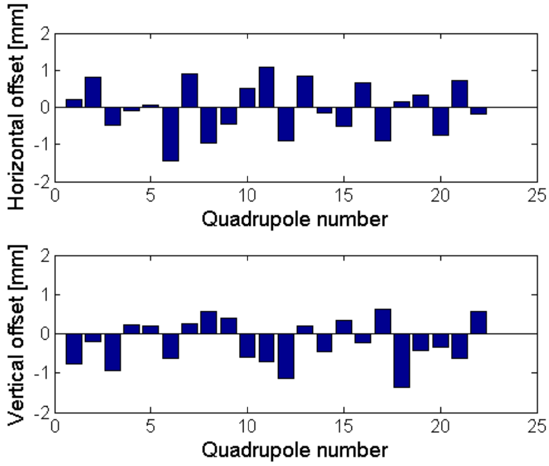

Figure 5: Results of beam-based alignment measurement.

ORBIT CORRECTION

The Linear Optics from Closed Orbits (LOCO) algorithm [8] was used to fit the booster AT model to the machine. A simple implementation of LOCO was developed using the Levenberg-Marquardt nonlinear least squares optimization algorithm to minimize the chi-squared function of the difference between the model and measured response matrices. Quadrupole strengths and horizontal and vertical corrector gains were varied in the fitting procedure, and a comparison of the best fit to one column of the response matrix is shown in Figure 6.

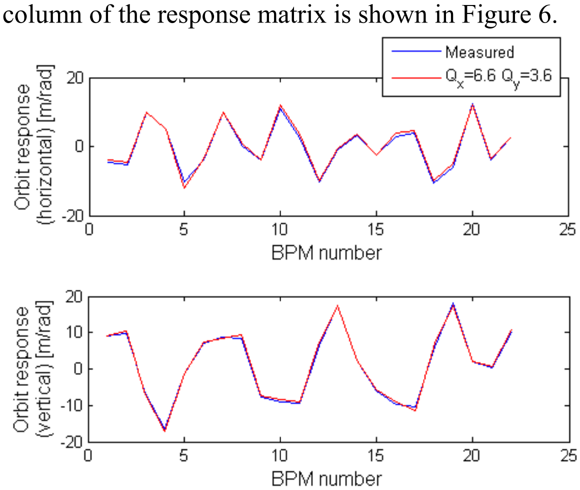

Figure 6: Orbit response and fitted model.

The best-fit tune, $Q_x = 6.6$, $Q_y = 3.6$ is consistent with the fractional tune measurements, and also gives the integer tune value. The fitted model was used to calculate the noise-free response matrix used for orbit correction, and tests with slow orbit correction confirmed that the response matrix measured in this way could be used to correct the orbit.

A fast orbit feedback (FOFB) application has been developed using the corrector responses measured in this way. The disturbance spectrum of the beam in the absence of any fast correction is shown in Figure 7, showing significant noise content between 15 and 50 Hz

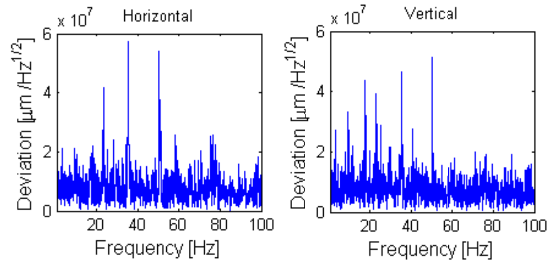

Figure 7: Noise spectrum of stored beam.

The uncontrolled and controlled integrated beam motion is shown in Figure 8. Use of the booster FOFB suppresses beam motion for frequencies up to the controller bandwidth of 227 Hz. Work is currently focused on improving the tuning of the controller and, in particular, extending the closed loop bandwidth while maintaining stability in the presence of uncertainties in the responses of the corrector magnets.

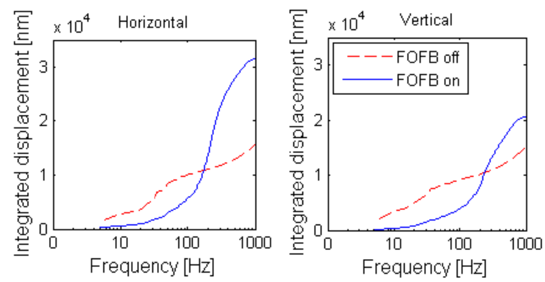

Figure 8: Integrated beam motion with and without FOFB.

SUMMARY

A 100 MeV stored beam mode of operation has been developed for the Diamond booster and is available for routine operation when required. Decaying beam can be stored with a lifetime of several minutes. This lifetime is sufficient to carry out detailed measurements of beam parameters and corrector response, allowing a fast orbit feedback application to be developed and tested. Investigations are continuing into orbit correction and control algorithms.

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