THE FIRST EIGHTEEN MONTHS OF TOP-UP AT DIAMOND LIGHT SOURCE

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Abstract

Diamond Light Source has delivered beam for users exclusively in top-up mode since late 2008. The effect of insertion devices, pulsed magnet stability and storage ring beam optics on top-up reliability and performance is examined and the top-up procedure is detailed.

TOP-UP AT DIAMOND LIGHT SOURCE

Diamond Light Source is a 3 GeV third-generation light source with a 561 m storage ring, a full-energy booster and a 100 MeV pre-injector linac. Diamond currently has 14 normal conducting insertion devices, 10 of them in-vacuum undulators, and 2 superconducting wigglers. User operation began in decay mode in January 2007. In October 2008, following a safety study and optimisation of the timing and injector systems [1], Diamond began top-up. In top-up, a small number of single bunches are regularly injected into specific buckets of the storage ring to maintain a constant beam current and fill pattern; this offers users a higher average beam current, with constant flux on mirrors and sample, and allows machine operation with constant heat load on all components and a greatly reduced range of operation of storage ring diagnostics.

Top-up involves injection of beam into the storage ring with open beamline shutters and closed insertion devices and so consistently high injection efficiency is needed to guarantee personnel safety and to avoid demagnetisation of IDs. Top-up is soft-interlocked to stop when injection efficiency falls below 50% or lifetime drops below 10 hours. In routine operation, efficiency is 80%, measured from an ICT near the start of the BTS transfer line to the storage ring, and lifetime is generally 15 to 20 hours, depending on machine configuration. Top-up is hard-interlocked to prompt and integrated radiation, beam energy, minimum ring current and BTS magnet currents.

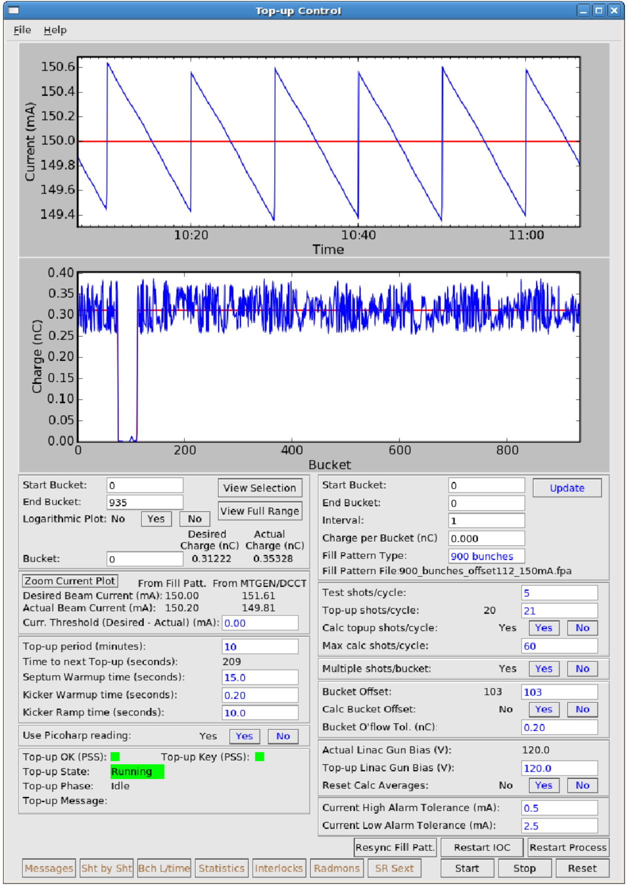
Typical top-up bunch charge is 0.15 nC, from slightly over 0.3 nC generated at the linac with the majority of the losses in the early part of the LTB transfer line. Around 20 single bunches are injected at 5 Hz each 10-minute top-up cycle. Beam current has been maintained at values between 150 mA and 250 mA.

THE TOP-UP APPLICATION

The 936-bucket storage ring can be filled automatically to any programmed pattern. Usually a two-thirds or three-quarters flat fill is used, and a hybrid fill with an additional intense single bunch can be provided on demand. Initial fill is carried out largely in multibunch mode, with an optional final single bunch stage. Beamline shutters are closed for the fill and in-vacuum insertion device gaps are set to a minimum of 7 mm. Once stored beam has been established, IDs are handed over to user control, shutters are opened and top-up is launched.

The top-up cycle starts with 3 GeV test shots fired into a beam-stop in the BTS transfer line. If test shot energy is correct and transfer efficiency from linac to BTS is high enough, the dipole directing beam to the storage ring is energised and the storage ring injection septum and booster extraction septa are warmed up: 15 seconds is allowed for the septa to settle. The kickers require one warm-up pulse. The linac gun and injector timing are then synchronised to inject single bunches into the buckets identified as having the greatest charge deficiency relative to the target fill pattern. The number of injected shots is calculated from bunch charge and injection efficiency. The BTS dipole is de-energised at the end of injection.

Top-up is controlled by a Python application which synchronises timing and diagnostics and monitors soft interlocks. The graphical interface is shown in Figure 1.



Start Bucket: 0
End Bucket: 935
Logarithmic Plot: No

	Desired Charge (nC)	Actual Charge (nC)
Bucket: 0	0.31222	0.35328

	From Fill Patt.	From MTGEN/DCCT
Desired Beam Current (mA):	150.00	151.61
Actual Beam Current (mA):	150.20	149.81

Curr. Threshold (Desired - Actual) (mA): 0.00
Top-up period (minutes): 10
Time to next Top-up (seconds): 209
Septum Warmup time (seconds): 15.0
Kicker Warmup time (seconds): 0.20
Kicker Ramp time (seconds): 10.0
Use Picoharp reading: Yes
Top-up OK (PSS): 🟩
Top-up Key (PSS): 🟩
Top-up State: Running
Top-up Phase: Idle
Top-up Message:

Start Bucket: 0
End Bucket: 0
Interval: 1
Charge per Bucket (nC) 0.000
Fill Pattern Type: 900 bunches
Fill Pattern File:900_bunches_offset112_150mA.fpa
Test shots/cycle: 5
Top-up shots/cycle: 20 21
Calc topup shots/cycle: Yes
Max calc shots/cycle: 60
Multiple shots/bucket: Yes
Bucket Offset: 103 103
Calc Bucket Offset: No
Bucket O'flow Tol. (nC): 0.20
Actual Linac Gun Bias (V): 120.0
Top-up Linac Gun Bias (V): 120.0
Reset Calc Averages: No
Current High Alarm Tolerance (mA): 0.5
Current Low Alarm Tolerance (mA): 2.5

Figure 1: Graphical interface to the top-up tool. The two plots show recent current record and fill pattern.

Storage ring fill in multibunch mode results in a ragged fill pattern because of the rise-time of the bunch train charge [2], but the precise targeting of underfilled buckets during top-up smooths out the fill in a matter of hours as shown in Figure 2.

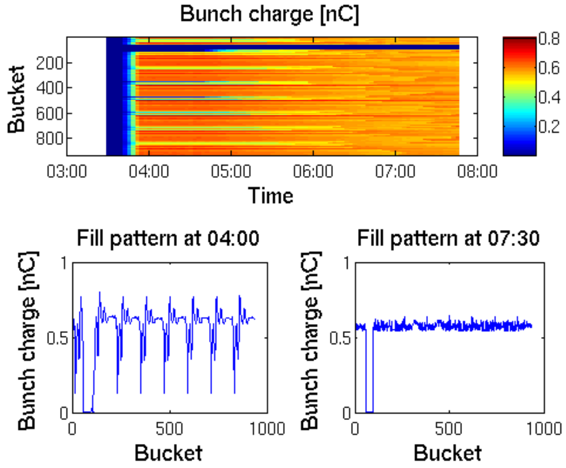


Figure 2: Development of fill uniformity during top-up

PULSED MAGNET STABILITY

The Diamond injection scheme consists of four fast kicker magnets placed symmetrically around the centre of the injection straight to create a closed beam bump, facilitating injection through a septum at the centre of the straight [3]. Top-up efficiency and residual kick are critically dependent on the performance of these pulsed magnets. A slow decay of injection efficiency caused by injection septum current drift became apparent following the establishment of top-up operation, and was initially corrected by trimming the septum current demand when the injection efficiency fell much below 70%. Figure 3 shows a three day record of unbroken top-up from 2009 demonstrating the dips in injection efficiency.

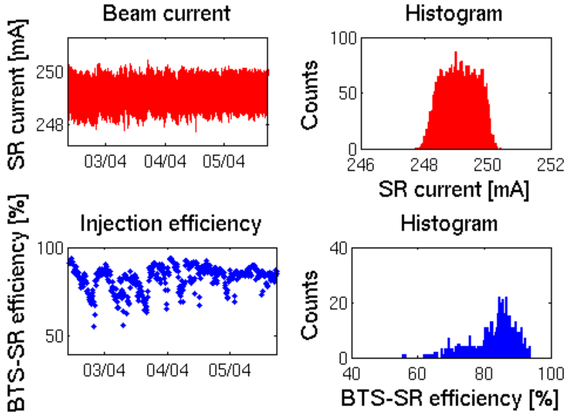


Figure 3: Top-up in 2009 with manual septum correction

Tests with a duplicate pick-up line revealed that the cause of the septum current pulse control fault was a drift in the measurement of the delivered current pulse and so the entire pick-up line was rebuilt, including a new current transformer and cable and connectors. This corrected the pulse amplitude feedback problem and stabilised top-up. Recent results of a five-day continuous run are shown in Figure 4, showing BTS-to-SR injection efficiency consistently over 80% apart from one occasion when top-up occurred during a booster re-optimisation procedure carried out to increase LTB-to-booster transfer efficiency.

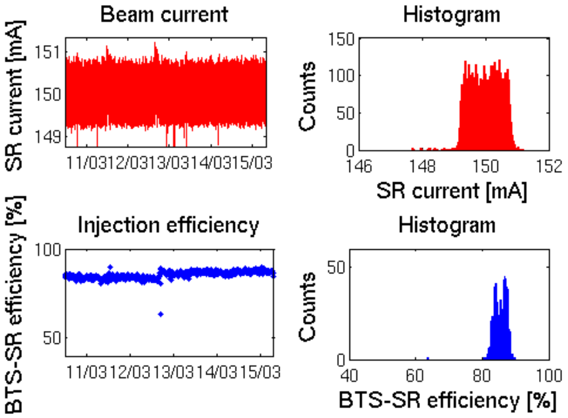


Figure 4: Top-up in 2010 with stabilised septum control

The storage ring kickers were designed to give identical pulses [4], however it became apparent during 2009 that kicker current pulse shapes changed during operation, resulting in increased disturbance of the stored beam on injection. In the worst cases, kicker mismatch became enough to kick out stored beam on injection. Pulse shape changes were caused by damage to carbon film resistors in the pulse-shaping circuit, and so in early 2010 these were replaced by more robust wire-wound resistors. No pulse degradation has been observed since this change.

INSERTION DEVICE EFFECTS

The minimum operating gap of the in-vacuum insertion devices was reduced in 2009 from 7 mm to 5 mm. Injection magnets and collimators in the injection straight were reset to accommodate this change, but a reduction of injection efficiency was still seen as IDs immediately after the injection straight closed. Figure 5 shows the drop in efficiency seen during the first extended closure of the ID in straight 4 below 7 mm during user beam.

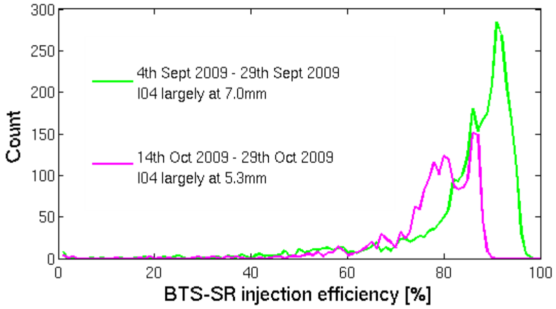


Figure 5: Efficiency drop with I04 closure to 5.3 mm

It became clear through 2009 that injection efficiency could be restored by dropping the horizontal tune of the storage ring from 0.225 towards 0.210. This method, however, failed when the kicker pulse match degraded. A tune scan in the horizontal and vertical plane is shown in Figure 6, revealing a region of kick-out parallel to the $3Q_x+Q_y=1$ resonance for badly matched kickers. This effect is absent for well matched kickers.

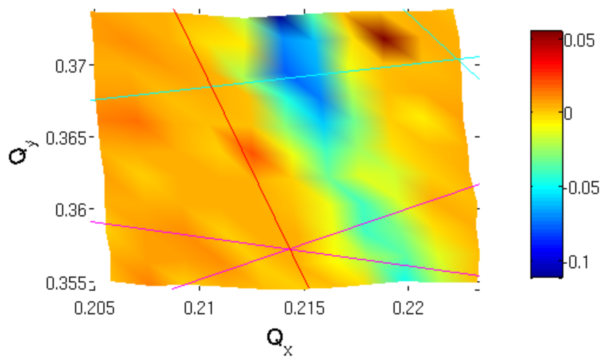


Figure 6: Beam kick-out with badly matched kickers. All in-vacuum insertion devices were at 5 mm.

Even with no kick-out of the beam, the effect of the resonance is evident, with better injection efficiency on the left side of the resonance shown in Figure 7. Dynamic aperture is also measured to be smaller on the right side of the resonance and decreases as IDs close.

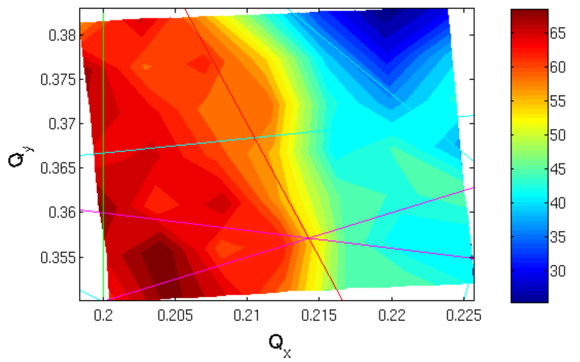


Figure 7: Injection efficiency with no kick-out. All in-vacuum insertion devices were at 5 mm.

Injection degradation in this case is related to the crossing of the resonance by the injected bunch. Time-resolved tune measurements obtained with TMBF show that tune of an injected bunch is initially to the left of the resonance because of the off-axis injection and the tune then rapidly crosses over the resonance to meet the stored beam tune.

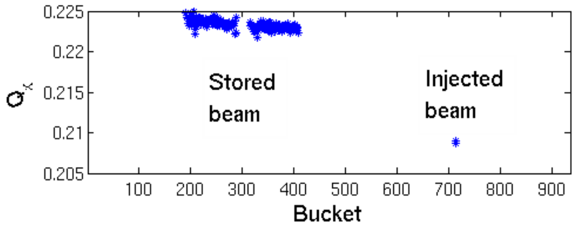


Figure 8: Horizontal tunes of stored beam and beam injected into the storage ring over the first 10 turns following injection. Vertical measurements are similar.

To avoid this resonance-crossing on injection, the working point of the storage ring has been moved from Q_x/Q_y = 0.225/0.363 to 0.205/0.360. There is now no significant reduction in dynamic aperture as IDs close to 5 mm and decrease in injection efficiency is greatly reduced, as seen in Figure 9.

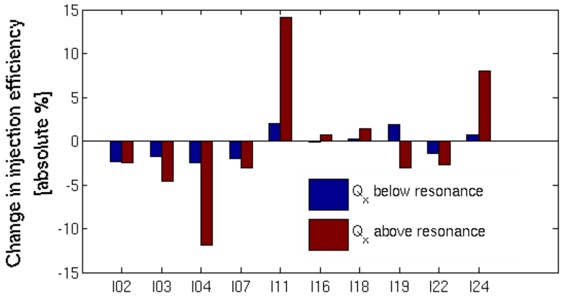


Figure 9: Change in injection efficiency as IDs are closed to 5 mm for the new (blue) and old (red) working points.

REDUCTION OF RESIDUAL KICK

A gating signal is provided to beamlines to enable a mask of injection disturbance; work has however continued to reduce the residual kick on the stored beam on injection. Following any work on the kickers, the four magnets can be rapidly tuned to give the residual kick seen in Figure 10, measured on a BPM at β_x=11.95 m/rad.

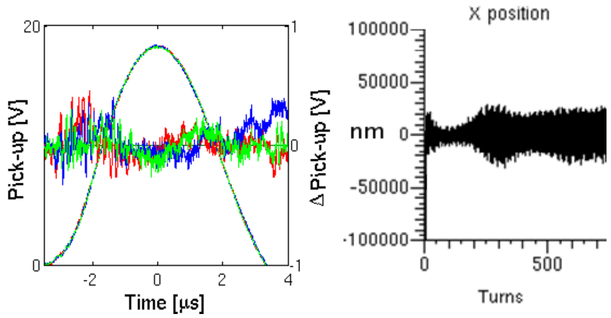


Figure 10: Matched kickers and minimum residual kick

Use of turn-by-turn data to quantify residual kick at these low values is limited because of averaging of bunch positions around the ring, but the residual kick is low, generally below 1 mm peak-to-peak for user operation.

PRESENT STATUS AND SUMMARY

Diamond Light Source has operated in top-up mode for 18 months, maintaining a variety of fill patterns for users. All ten in-vacuum IDs can be closed to 5 mm without impacting performance, and continuous top-up runs of up to five days uninterrupted beam have been delivered.

Injection septum current drift, kicker pulse degradation and resonance crossing of injected beam were identified as issues impacting injection efficiency and residual kick during top-up. All three issues have been addressed, and Diamond presently operates exclusively in top-up mode with BTS-SR injection efficiency consistently over 80% and stored beam residual kick less than 1 mm.

REFERENCES

[1] R. P. Walker et al, EPAC'08, p. 2121.
[2] C. Christou et al, PAC'07, p. 1112.
[3] S. Smith et al, EPAC'04, p. 2420.
[4] V. C. Kempson et al, EPAC'06 p. 3341.