RECENT DEVELOPMENTS AT DIAMOND LIGHT SOURCE

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Abstract

Recent developments at Diamond Light Source are presented, including its operational performance, introduction of top-up operation and reduction of in-vacuum undulator gaps to 5 mm.

OPERATIONAL PERFORMANCE

Diamond Light Source commenced routine operation in January 2007 [1]. The scheduled operating hours have steadily increased since then (see Table 1), although the original target of 5000 h for the 3rd year of operations has not been met because of the continuing pace of installation of insertion devices (IDs) and front-ends for Phase II beamlines.

Table 1: User mode operating statistics (excluding start-up and machine development shifts). Numbers in brackets refer to the first 4 months of 2009.

Year	Scheduled Hours	Up-time (%)	MTBF (h)
2007	3160	92.3	10.6
2008	4092	94.9	14.5
2009	4656 (*1536*)	(*94.9*)	(*14.8*)

During the first year of operation the beam current during user shifts was 125 mA, compatible with beamline needs at that time. From Jan. 2008 the beam current was increased in 25 mA steps up to 175 mA, still with only one superconducting cavity in operation. Even though the second cavity was installed in Mar. 2007, reliable two cavity operation was not established until Jun. 2008, because of the limited time that had been available for conditioning the second cavity with beam. Thereafter the beam current was increased up to the present operating level of 250 mA in Oct. 2008. The beam current has stayed the same since then, partly because of higher than expected He boil-off in the superconducting wiggler, and partly for reasons concerning reliability.

Up-time and reliability have improved since the first year of operation (Table 1) but MTBF in particular is not as high as desired. The trips have a wide variety of causes, with the RF system accounting for roughly half of them. Since reliability is more important to users than a modest increase in current to the design value of 300 mA, we have decided to postpone increasing the beam current. There is some evidence that changing the RF conditions has contributed to the relatively high number of cavity trips, as well as making it more difficult to establish trends. The storage ring has however been tested at 300 mA and there are no other issues in increasing the current when required.

Diamond operates routinely at 250 mA with 686 contiguous bunches filled out of 936, and sometimes in "hybrid mode" with a high charge (6 nC) single bunch in the middle of the unfilled section. The only exception has been a recent period of several days when operating in low-alpha mode for time resolved experiments [2].

TOP-UP OPERATION

It was always planned that Diamond would operate in top-up mode, however it was only during 2007/2008 that we undertook a safety analysis, which included extensive simulations and measurements to evaluate the potential risk of high radiation doses being generated around a beamline due to all possible failure modes [3,4]. As a result of these studies an extra hardware interlock was implemented, in addition to the one originally foreseen which only permits top-up operation in the presence of a stored beam, to ensure that the injection occurs on-energy, by means of interlocks on the current of two dipole magnets in the transfer line as well as the storage ring dipole magnets.

Radiation safety in top-up mode is maintained by these hardware interlocks which are tested at the beginning of each run, but in addition we have also implemented checks in the top-up control programme which inhibit top-up if the lifetime is less than 10 hours, storage ring injection efficiency is less than 50% or other parameters which would adversely effect top-up are out of limit. The radiation monitors on each beamline will also intervene and close the relevant beamline shutter if the instantaneous dose, or dose integrated over 4 hours, exceeds the prescribed limits.

Following successful tests during Machine Development periods, top-up during User Mode started on Oct. 28th 2008 for a trial period of 3 days. Given the positive reaction from users, top-up then became the standard operating mode for user shifts.

As determined by the beamline scientists, top-up injection occurs at fixed intervals of 10 minutes. Multiple single-bunch injection is used, typically 20-30 shots per cycle, at 5 Hz injection rate. On each cycle the control program ensures that bunches with the largest deviation in current are filled, so that any arbitrary fill pattern can be maintained. With a beam lifetime of typically 24 h, the beam decays by 1.7 mA (0.7 %) in the 10 minutes between injections. Due to variability of the injected current however the typical stability achieved so far has been about 2 mA (0.8 %).

Top-up has now operated reliably for four runs. The longest period of top-up operation without a beam trip is currently 105 hours. Although not resulting in beam loss, top-up does occasionally fail for a variety of reasons. These failures however usually only affect a small number of cycles (1-4) and are invisible to users. The main causes of top-up failures and their incidence in the last four runs are given in Table 2. A marked improvement can be seen after the first two runs as various problems were rectified.

Table 2: Analysis of Top-Up Failures

Fault	Run 9-08	Run 1-09	Run 2-09	Run 3-09
Linac	4	14	5	3
Booster	9	1	1	1
Linac to Booster transfer efficiency	2	5	0	3
Booster to Storage Ring transfer efficiency	7	1	2	1
Communication errors	4	2	2	1
Others	6	2	0	0
TOTAL	32	25	10	9

One of the well-known benefits of top-up operation is improved beam stability. Although the beam position is always maintained by the global Fast Orbit Feed-Back system to sub-micron level at the electron BPMs [5], physical movement of the BPMs themselves due to thermal effects results in movement of the photon beams. In top-up mode this is eliminated, and figure 1 illustrates the resulting marked improvement in photon beam stability measured using one of the X-ray BPMs that are installed in each ID beamline (at fixed ID gap).

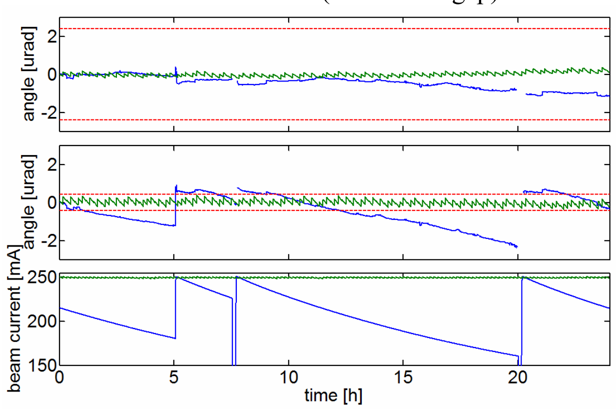

Figure 1: Variation of horizontal angle (upper), vertical angle (middle) and beam current (lower) with time, in decay (blue) and top-up modes (green). Red lines indicate 10% of the respective beam divergence (1% coupling).

Despite the fact that there is some transitory disturbance of the stored beam at the ± 150-250 μm level due to the injection kickers, most of the 13 currently operating beamlines do not need to gate their data acquisition. Two beamlines inhibit data taking during injection by software, making use of an EPICS process variable which counts down to the next injection. Several beamlines are however planning more sensitive experiments in the future that will make use of hardware gating signals that are available on all beamlines.

INSERTION DEVICE GAPS

Diamond currently has 10 installed in-vacuum undulators, with several more planned. The initial specification for these devices was a minimum operating gap of 7 mm, with a future goal of 5 mm. Given the strong desire of some beamlines in particular to reduce the gaps, either to enhance output at the highest photon energies, or extend the tuning range of the 3rd harmonic to lower photon energies, a campaign of measurements has therefore been started to understand the consequences of reducing the gaps in terms of injection efficiency, beam lifetime and beam losses.

Concern about possible radiation damage to the undulators has led us to take a cautious approach and try to understand the distribution of beam loss around the ring. Losses are measured using a set of commercial PIN-diode based counting modules, in particular those located on the girders following each ID. Initial observations showed quite large increases in losses as ID gaps were reduced, and so it was decided to close further the horizontal and vertical collimators which are located near the ends of the injection straight. Measurements showed that they could be closed to ±10 mm horizontally and ±3 mm vertically (compared to previous settings of ±14 mm and ±4 mm respectively) without significant effect on lifetime or injection efficiency (which is somewhat variable but generally > 80%).

Under these conditions, with stored beam, closing an individual ID to 5 mm gap has little effect on lifetime; closing all devices causes a reduction in lifetime from about 23 h to 20 h, the cause of which is not understood, but is small enough not to be of particular concern. The beam losses in the ID straights generally increase at lower gaps, particularly below 6 mm, as shown in fig. 2, but vary significantly from ID to ID.

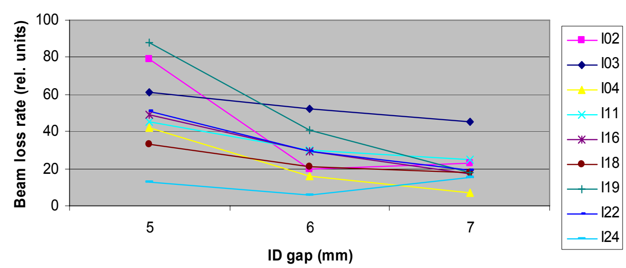

Figure 2: Beam loss rates measured downstream of the IDs as a function of gap.

Most IDs can be closed to 5 mm without affecting injection efficiency, however one device in particular (I04) does have a stronger effect below 6 mm gap, reducing the efficiency from 80% to 67% at 5 mm gap. With the three devices that most urgently require smaller gaps (I02, 3 and 4) closed to 5 mm, the injection efficiency is still at an acceptable level of 60%. The measured beam losses during injection are even more difficult to understand than the stored beam losses. For example, closing one ID not only increases the losses in that straight, but also does in some other straights, as well as at the collimators, even if the overall injection efficiency is unchanged. Comparing the loss rates with stored beam and during injection however shows that the total losses are dominated by the stored beam losses and so these effects are less of a concern.

Further measurements are planned to try to understand the differences in behaviour between the IDs and to minimise the beam losses. Nothing we have found so far however precludes operation at smaller gaps. The loss measurements can at best only be qualitative, since the actual dose received by the undulator magnets, which are in-vacuum and therefore inaccessible, is unknown. In any case all of the existing devices have been constructed with Sm2Co17 material which is less sensitive to radiation damage than NdFeB. Four beamlines have therefore been allowed control of ID gap down to 5 mm during normal operation, one beamline to 6 mm gap (as required), while one further beamline is carrying out tests to determine its minimum gap requirements.

OTHER ID DEVELOPMENTS

A second superconducting multipole wiggler has recently been installed and is in the process of being commissioned with beam. This device, constructed by BINP, Novosibirsk, is a more advanced design than the first wiggler, also constructed by BINP, and reaches a peak field of 4.2 T with 48 mm period length, compared to 3.5 T and 60 mm period.

The next ID straight to be installed will contain a pair of hybrid multipole wigglers. The vacuum vessel for this straight has already been installed, a 4.5 m long NEG coated Al extrusion of the ESRF type with internal (external) vertical dimension of 8 (10) mm [6]. This is the smallest fixed vertical aperture in the ring, however no problems were experienced with its installation and vacuum levels recovered very quickly.

After that, a cryogenic permanent magnet undulator will be installed, which is currently under construction by Danfysik A/S.

Subsequent beamlines require in addition to the IDs extensive changes to the storage ring arcs. Beamline I10 requires a fast switching of the polarisation, which will be achieved using two APPLE II devices and a set of 5 pulsed magnets, operating at 10 Hz. In order to be able to accommodate this in a standard straight section, 4 of the kickers will be mounted on the arc girders upstream and downstream of the ID. To do this in the most efficient way, the kickers will be installed on the spare girders and then the complete girders will be swapped out. The process of swapping a girder has already been carried out successfully when a modified dipole/crotch vacuum vessel with wider exit port for an IR beamline was installed in November 2008.

Beamline I13 requires two in-vacuum undulators with the smallest possible gaps for its Imaging and Coherence branches. The lattice will therefore be modified by installing an extra quadrupole at the upstream and downstream ends of the straight, as well as two quadrupoles in the middle of the straight, so as to be able to produce two vertical beta minima at the ID locations [7]. An additional feature of the scheme is that it produces a negative slope of the horizontal beta function at one of the ID locations, thereby focusing the radiation at the desired downstream location. To accommodate the extra quadrupoles on the arc girders will require two girder swaps in this case also. Finally, beamline I09 has similar requirements and so will also require two girder swaps. A series of 4 week shutdowns are therefore foreseen in 2010/2011 for the girder changes.

REDUCTION IN BEAM VIBRATIONS

Previous work showed that the biggest contribution to the beam motion was at close to 25 Hz, due to the main demineralised water pumps [8]. A number of measures have therefore been undertaken to rectify the problem, by realigning them, releasing tie-bars, freeing pipe hangers etc., which has resulted in the elimination of this component to the vibration spectrum, as shown in fig. 3. The next items to be tackled will be the air handing units for the control and instrumentation areas, which give the next largest contribution to the beam motion at 18 Hz.

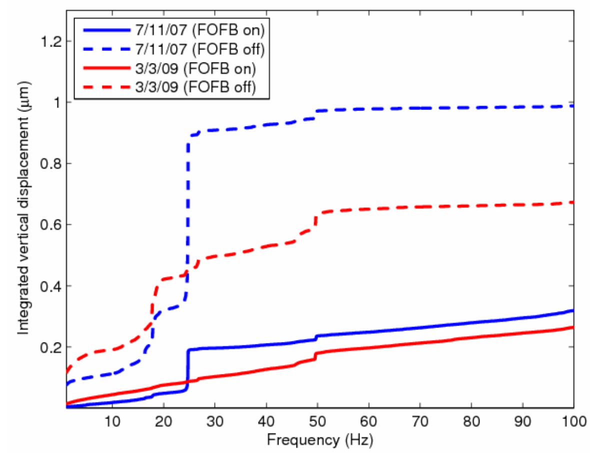

Figure 3: Beam motion in the vertical plane, integrated from 1 Hz to the indicated frequency, with fast orbit feedback off (dotted lines) and on (solid lines); earlier data (blue) and recent data (red), after intervention on the water cooling pumps.

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