COMMISSIONING AND STATUS OF THE DIAMOND STORAGE RING

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Abstract

The commissioning of the Diamond storage ring at 3 GeV, as well as the current status and future plans, are described.

INTRODUCTION

The construction phase of Diamond, the UK's new medium-energy 3rd generation synchrotron light source [1,2] concluded at the end of December 2006. Diamond has now entered the operational phase, with first external users starting at the end of January 2007, in line with the original programme. The main parameters of Diamond are given in Table 1.

Table 1: Main parameters of the Diamond storage ring.

Energy	3 GeV
Circumference	561.6 m
Lattice	24-cell DBA
Straight sections	6 x 8 m, 18 x 5 m
RF frequency	500 MHz
Nominal current	300 mA
Nominal rms emittances (H,V)	2.7, 0.03 nm rad
Nominal rms energy spread	0.096 %

This report will concentrate on the recent commissioning of the storage ring at the full energy of 3 GeV which began in September 2006. The earlier commissioning of the 100 MeV linac (August-October 2005) and 3 GeV booster (December 2005 – June 2006), as well as the initial phase of storage ring commissioning (May 2006), were described at EPAC 2006 [2-5].

The first phase of storage ring commissioning took place at 700 MeV, because of the lack of water cooling at that time for both magnets and radiation absorbers. The low energy made commissioning very difficult, however it did prove possible to accumulate a current of 2 mA. Following this period the ring was shut-down for 3 months both to complete the water cooling systems, as well as to install the insertion devices, and further front-ends. By the beginning of September all seven Phase I insertion devices had been installed.

Commissioning at 3 GeV began on the evening of the 4th September 2006. Operation was restricted to outside normal working hours until the radiation shielding had been verified. On the first evening the beam was circulated for 5 turns, with correctors, sextupoles and RF off. The next evening 120 turns were obtained, with sextupoles on. The following evening the RF was turned on and a beam of 2 mA was accumulated. In 3 evenings therefore we had accomplished what had taken a month at 700 MeV, because of calibration, stability and other beam dynamics issues [2].

At that stage the current was deliberately limited at 2 mA until cooling water and interlocks on the radiation absorbers had been fully tested. Two days later this work had been carried out and beam was accumulated up to 10 mA. Another limit was placed at this level since the orbit interlock for protecting the vacuum vessel in case of mis-steered photon beams was not yet in operation. Nevertheless the current was sufficient to allow progress to be made with closed orbit correction and optics optimisation. Once the orbit interlock was operational the current was gradually increased, carefully checking for beam instabilities and monitoring vessel temperatures and vacuum pressures. By the beginning of October, 60 mA had been reached and the target for initial operation of 100 mA was achieved on Nov. 11th. Further progress was limited by the time available for high current operation and RF conditioning, since an increasing amount of time was devoted to beamline commissioning. First light was let into a beamline optics hutch on Oct. 12th, and regular daytime beamline commissioning started on Oct. 23rd.

ACCELERATOR PHYSICS

Closed-orbit

Initial correction of the closed orbit quickly reduced the error to the level of 0.7 mm rms in both planes, but no less. A "beam based alignment" (BBA) was then carried out to determine the offset between the centre of each beam position monitor (BPM) and the magnetic centre of the nearest quadrupole magnet.

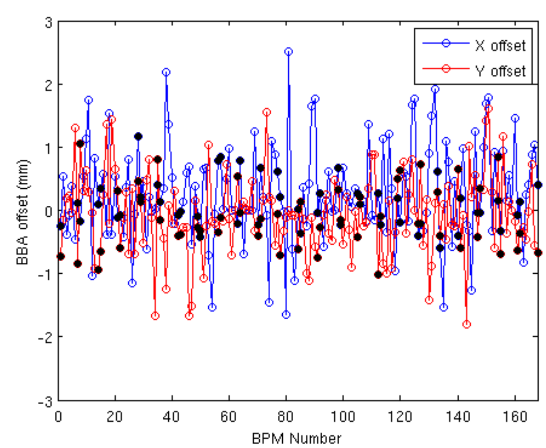

Figure 1: BPM-quadrupole offsets; black dots denote "primary" BPMs.

The Accelerator Toolbox Middlelayer routine "quadcenter" [6] was used for this task. A complete scan of all 168 BPMs required 8 hours. The first measurement did not result in a very accurate determination of the offsets, but nevertheless when the offsets were taken into account the closed orbit could be improved. A further series of iterations was then carried out, each time reducing the residual closed orbit until an orbit with less than 1 µm deviation at each BPM was able to be produced, using all of the eigenvalues of the response matrix, and all 168 correctors in each plane. Using only 96 correctors, rms orbit errors of 60 µm horizontal and 40 µm vertical could still be achieved, with modest corrector strengths (<0.3 mrad Horiz., <0.15 mrad Vert.), which is further positive evidence for the correctness of the BBA approach.

Fig. 1 shows the final BPM-quadrupole centre offsets. These values might appear quite large, but are not unreasonable given the uncertainty in the mechanical positions of the BPMs as well as the uncertainty of the electrical centres of the BPM pickup blocks, including cable and electronic differences. Some larger errors have been found to be due to variations of cable length within a set of 4, which will be corrected in due course. Fig. 1 shows that the offsets are generally smaller at the "primary" BPMs, which are located on either side of the insertion device straights, but this is probably because of the smaller calibration factor, rather than the better mechanical positioning accuracy.

Following BBA it was discovered that the correctors could be switched off to allow the "bare orbit" to be measured, which gave a result of 4.8 mm rms horizontal and 3.1 mm rms vertical, which is reasonably consistent with the specified quadrupole positioning accuracy.

Closed-orbit Stability

A slow orbit feedback has been implemented at the MATLAB level which currently acts every 5 seconds and maintains the orbit correction at the BPMs to below 0.5 µm rms in both planes. Without the orbit correction, the orbit deviation grows to about 1-2 µm rms within 15 minutes. This orbit stability has also been confirmed through first observations on the XBPMs in the front ends.

The stability of the beam at higher frequencies is of the order of 3-4 µm rms horizontal and 0.8 µm rms vertical when measured at one of the primary BPMs, integrated over the frequency range 0-1 kHz. The major contribution to this is a disturbance at 24.9 Hz. Vibration measurements have detected this both in the ground and on one of the 3 girder types (Girder 1). The second biggest contribution comes from frequencies in the 16-20 Hz range which appear to be associated with resonances in Girders 2 and 3. Where possible the vibration sources will be identified and reduced, the fast-orbit feedback that is under development (see below) should however have no difficulty in combating them.

Linear Optics Optimisation

Measurement and optimisation of the linear optics has benefited greatly from the LOCO program [7]. The first analysis revealed a beta function error of ± 40% in both planes. The first correction reduced this to below 15%, and after a series of iterations, the quadrupole settings calculated by LOCO have reduced this error to less than 1% in both planes, see Fig. 2.

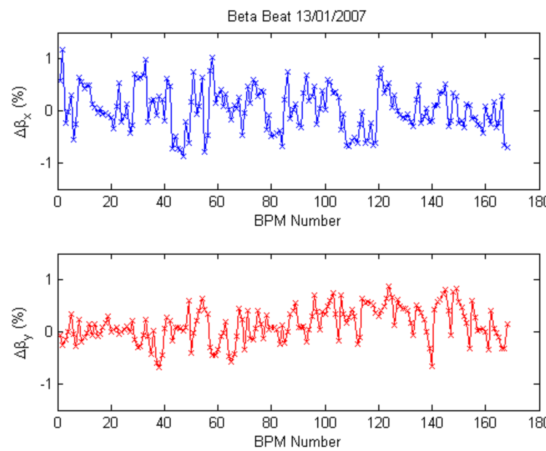

Figure 2: Beta function errors after LOCO correction.

The changes to the quadrupoles required to correct the optics were up to 5% in absolute terms, however, the initial calibration of the magnets was known not to be very accurate. Within magnet types, the relative variations are never larger than 2%, consistent with results found on other machines.

Following LOCO correction the measured dispersion function is also in good agreement with the model.

Emittance, Energy Spread and Coupling

Two X-ray pinhole cameras are located at source points with different lattice functions, so allowing the beam emittances and energy spread to be deduced. Current measurements give a horizontal emittance in the range 2.6-2.8 nm rad and an energy spread of 0.11%, close to the nominal values (see Table 1), given some uncertainty in the knowledge of the optical functions at the two different source points.

LOCO has also been used to correct for linear coupling using the skew-quadrupole correction coils mounted on the sextupole magnets. With skew-quads off, the closest approach of the tunes was ΔQ = 0.0067, which predicts an emittance ratio from betatron coupling at the nominal working point (assuming zero vertical dispersion and a single resonance approximation) of 0.13%. The measured emittance ratio using the X-ray pinhole cameras was 1.3%, indicating that vertical dispersion is dominant. Using the skew-quad correction predicted by LOCO resulted in a very small tune separation of ΔQ = 0.0004 and hence negligible betatron coupling and a measured emittance ratio of 0.17%. It is planned to use the skew-quadrupoles to stabilise the emittance ratio at a fixed value for user operation in the near future.

Instabilities

Multibunch instabilities, both horizontal and vertical, evidenced by the appearance of betatron sidebands around the orbit harmonics in the beam spectrum, became apparent as soon as the stored current began to be increased. In fact, the onset of vertical instability has been observed as low as 17 mA at zero chromaticity, a factor of 2 lower than the predicted threshold for the resistive wall instability.

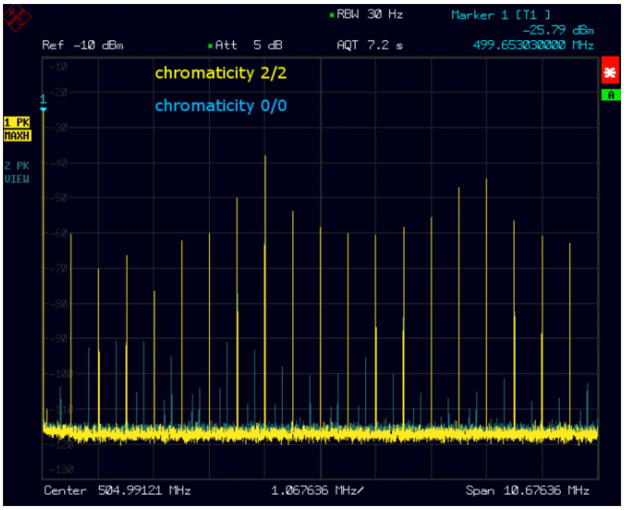

Figure 3: Spectrum analyser signal at 60 mA with zero and +2 chromaticity in both planes and 2/3rd filling. The left-hand-side peak is the RF frequency, one division corresponds to twice the orbit frequency.

The threshold for instability increases as the chromaticity is increased in the relevant plane, but depends also on the percentage filling of the storage ring circumference – uniform filling requires the largest chromaticity to be stable, 1/3rd fill the least, with 2/3rd fill in-between. Fig. 3 shows an example of how positive chromaticity suppresses signs of the resistive wall instability at 60 mA. Currently for operation up to 110 mA with 2/3rd filling a chromaticity ($\Delta Q/\Delta p/p$) of +2 in both planes is sufficient to completely suppress instabilities. Further measurements are planned to characterise the effects of resistive wall and ions, the signatures of which have both been observed under different operating conditions.

Injection Efficiency

Injection efficiency initially was poor, but improved during the process of closed orbit and optics correction. The efficiency (from transfer line exit to stored current) is now typically 85-95%, and is being routinely monitored to determine reproducibility and as an early warning of parameter “drift”.

DIAGNOSTICS

All of the diagnostics systems are operational, with the exception only of some in the booster-to-storage ring transfer line. The digital BPM electronics in particular have proved to be extremely valuable during the various phases of commissioning, when the various modes, such as turn-by-turn (for obtaining the initial turns in the ring), slow acquisition (for closed orbit correction) and fast acquisition (for investigating orbit stability and later fast orbit feedback) have been used.

The resolution of the BPM system is well within specification and in line with previous laboratory tests. Beam current dependence has been observed at slightly higher values than expected from the laboratory tests and will have to be studied systematically by correlation with XBPMs and beamline diagnostics.

Pairs of XBPMs in 6 of the front-ends have been installed and calibrated versus insertion device gap. Initial measurements showed a measurement uncertainty of 500 nm for a 100 ms integration time. This means that enough resolution is available to observe beam stability as seen by the beamlines.

INSERTION DEVICES

Seven Phase I insertion devices (IDs) were installed before 3 GeV commissioning began in September and an 8th device (I22) was installed in the Dec./Jan. shutdown. Table 2 summarises the main properties of these devices. The maximum rms phase error refers to the main operating range between 5 and 10 mm gap, and is clearly better in the later devices compared to the first one (I02). All of the insertion devices have been commissioned and are in routine use for beamline commissioning; the in-vacuum devices are currently operating down to the initial minimum gap of 7 mm.

Table 2: Main parameters of the first 8 insertion devices.

Beam -line	ID type	Period (mm)	No. of Periods	Field [T]		Max. phase error (°)
				gap = 5mm	gap = 7mm	
I02	IN-VAC	23	85	0.92	0.70	3.9
I03	IN-VAC	21	94	0.86	0.64	3.1
I04	IN-VAC	23	85	0.92	0.70	2.8
I06	APPLE-II	64	33	0.94T (15 mm)		5.5
I15	SCW	60	24	3.5T		-
I16	IN-VAC	27	73	1.0	0.8	2.3
I18	IN-VAC	27	73	1.0	0.8	2.1
I22	IN-VAC	25	79	0.97	0.75	2.1

The uncorrected closed orbit change as a function of gap is of the order 20-25 µm for the in-vacuum undulators, and 50 µm for HU64. Trim coil settings have been determined as a function of gap (and phase in the case of HU64) and are now set automatically, which results in a residual orbit disturbance of about 1-2 µm rms. The SCW currents have also been adjusted so as to minimise the effect at full field, while the ramp-up of the wiggler field has been corrected to keep the orbit well within the beam position interlock threshold.

No other significant effects on the beam have been observed. The effect on the tunes are small, < 0.001 in the case of the in-vacuum undulators, < 0.004 for HU64 and 0.012 for the SCW. The SCW introduces a beta-beat of 11 %, which so far has not needed to be compensated. No effects on lifetime have so far been observed.

RADIATION PROTECTION

The storage ring tunnel shielding has been progressively verified under both injection and stored beam conditions so as to allow operation by day with unrestricted access around the tunnel enclosure. Currently there is no restriction on access with the ring operating at a current of up to 150 mA. Measured dose rate levels under stored beam conditions have generally been indistinguishable from background. Combined gamma and neutron radiation monitors around the outside of the tunnel will trip the injection if the measured dose rates exceed a set limit, however this has only occurred during the initial stages of commissioning.

RF SYSTEM

The storage ring is currently operating with a single RF cavity: the second cavity developed a leak before 3 GeV commissioning began and is currently under repair. The installed cavity is routinely operated with an accelerating voltage of up to 2 MV, however increasing the beam current above 80 mA has required dedicated conditioning time to overcome vacuum bursts in the vacuum space between the RF window and the cavity, and to condition the coupler between the waveguide and the cavity. The vacuum activity was particularly noticeable at discrete current levels, however the cavity appears to remain conditioned even when operated below the maximum current for extended periods. Additionally, re-conditioning following a complete warm up has been rapid. Other parts of the RF plant are working well, with little down-time. Despite the RF amplifier operating significantly below the specified maximum RF output power, the efficiency of the IOTs remains high. The low-level RF system controls amplitude and phase to within ± 0.1% and 0.1^{o} rms respectively, well within the specification.

VACUUM AND BEAM LIFETIME

At the start of 3 GeV commissioning in September 2006 the storage ring mean static gauge pressure was 4.5 10^{-10} mbar, and the pressure was relatively uniform around the ring apart from the injection straight with an average pressure of 6.5 10^{-9} mbar**.** Apart from 3 ID straights containing NEG-coated Al vessels and the diagnostics straight which had been baked out in-situ, the rest of the stainless-steel vacuum system had only been baked-out in sections prior to assembly on the girders, not in-situ [8].

Conditioning with beam has progressed according to expectations. The dynamic pressure rises have been more or less uniform around the storage ring, with no particular "hot spots". According to RGA scans the residual gas is typically >90% hydrogen without beam and >80% hydrogen with beam.

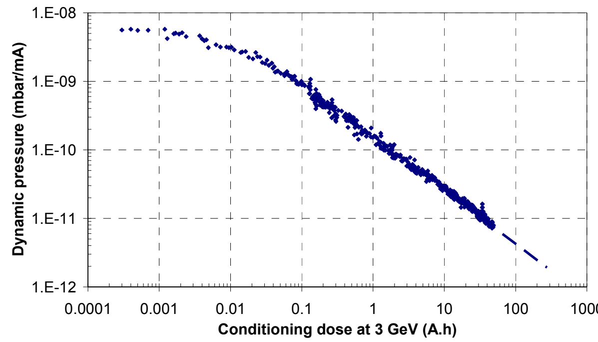

Figure 4: Dynamic vacuum pressure vs. beam dose.

Regarding the in-vacuum undulators, three of the initial five were baked-out in the ring, during which the NEG coated connecting vessels were also baked. The other two with stainless steel connecting vessels were only baked out in the lab. prior to installation. Interestingly, the vacuum performance of these two types is similar, both as regards static and dynamic pressure.

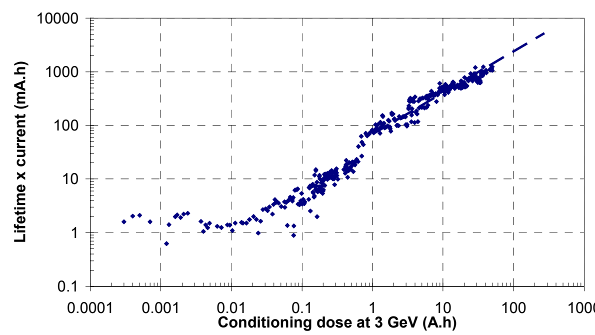

Figure 5: Beam lifetime-current product vs. beam dose.

Fig. 4 shows the average dynamic pressure as a function of beam dose, D, (i.e. integrated current) at 3 GeV which follows a $D^{-0.8}$ law apart from the initial stages of beam conditioning, typical of many other machines. After an accumulated dose of 50 Ah the dynamic pressure is currently 8.0 10^{-12} mbar/mA and the typical static pressure during short periods without beam is 4-5 10^{-10} mbar. After several weeks without stored beam, during a recent maintenance shutdown, the static pressure fell to 3.6 10^{-10} mbar. The static pressure in the injection straight is 2.5 10^{-9} mbar. The graph shows that after further conditioning the target pressure of 10^{-9} mbar at 300 mA after a dose of 100 Ah is close to being met.

Fig. 5 shows the current-lifetime product as a function of beam dose, which continues to increase, consistent with the lifetime being dominated by vacuum pressure. The marked step-change in lifetime around 0.7 Ah coincides with the 3rd beam-based alignment, which allowed the closed orbit to be corrected to <100 µm rms, and the working point to be moved to the nominal one. Lifetimes in excess of 10 h are currently achieved at 100 mA. The data are consistent with achieving the design specification of 10 h lifetime at 300 mA after approximately 100 Ah conditioning.

STATUS AND FUTURE PLANS

The storage ring and injection system are running reliably and providing regular "user beam" from 8 insertion devices, with up to 125 mA beam current, with a slow-orbit feedback in operation. During accelerator physics shifts a maximum of 160 mA has been achieved. The plan for 2007 is to provide at least 3000h of User Mode, in 10 Runs lasting between 2 and 3 weeks. One shutdown period (March/April) will be used to install the second cavity, after which the beam current will be gradually increased to 300 mA. Other shutdowns will be used to install the second module of HU64, two further in-vacuum IDs, and 4 front-ends.

Several upgrades are being developed during 2007 as described below.

Fast Orbit Feedback

A Fast-orbit feedback system is nearing completion. BPM data is transmitted via fast serial links into a series of VME crates where dedicated feedback processors perform the feedback calculations and write the resulting corrector magnet values directly through the VME bus into the power supply controller cards. In this configuration data from all BPMs is available at all locations via multiply redundant links, providing a great resilience against failure.

The current status is that all hardware has been installed, communication of orbits at fast acquisition rate (10,072 measurements per second) is running reliably, the 24 receivers in the power supply racks can record data (up to 100,000 orbits) and all processing tasks (calculation of correction, control loop, communication to power supplies) exist in software, ready for first use. First closure of the loop is expected in February.

Transverse Multibunch Feedback

To avoid the possibility of having to operate with excessively high chromaticity in order to reach 300 mA, and above, with possible negative consequences for lifetime, injection efficiency etc., a transverse multibunch feedback system is being developed, based on the Libera bunch-by-bunch system.

Kicker striplines (SLS-type) and extra pickup buttons are already installed in the diagnostic straight. The bunch-by-bunch feedback processors have been delivered and tested in the lab. The RF front-end has been assembled and tested as a system in the lab, and will be installed in February. First tests of data acquisition will occur in March. Development of the FPGA based feedback algorithm has started, in collaboration with the ESRF, and testing of feedback with beam is expected by mid 2007.

Top-up Injection

Provision of top-up injection has always been part of the design specification for Diamond, and has been taken into account in the design of the linac, booster magnet power supplies, timing system, personnel safety system etc. Detailed attention is now being given to the various studies and tests that need to be carried out e.g. localisation of beam losses with collimators, testing injection with IDs closed, radiation checks, testing safety interlocks etc., as well as safety documentation. It is currently envisaged that top-up will operate in multi-shot, single bunch mode, with injections at a fixed time interval. At 300 mA with 10h lifetime, injection every 2 mins will lead to a 1 mA current stability, which is considered adequate by users.

ACKNOWLEDGEMENTS

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