Commissioning of the Diamond Light Source storage ring vacuum system

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Abstract. The Diamond storage ring has been operating with a 3 GeV electron beam since September 2006 and 190 A.h of beam dose have been accumulated. The pressure in the storage ring is \(4.2 \times 10^{-10}\) mbar without beam, rising to \(7.9 \times 10^{-10}\) mbar with 125 mA of stored beam. Data on the storage ring vacuum performance and experience from commissioning and beam conditioning are presented.

1. Introduction
Diamond, the UK's new medium-energy 3rd generation synchrotron light source, has been operating with external users since January 2007. In the first 4 user runs of 2007, 1142 hours of user beam were delivered corresponding to an average uptime of 91%.

The main accelerator vacuum systems of Diamond are a 561.6 m circumference 3 GeV electron storage ring, a 158.4 m circumference booster ring and a 100 MeV Linac. 8 beamlines are operational, each with an associated insertion device and front end. Approximately 4 new beamlines per year will be installed and commissioned during the next few years of facility development.

The construction and installation of the Diamond storage ring and results from initial beam commissioning at 700 MeV have already been reported [1]. Commissioning at 3 GeV began in September 2006. A brief update on the vacuum system performance during the first part of 3 GeV beam operation has also been reported [2]. The Diamond storage ring is now well conditioned, having accumulated a 3 GeV beam dose of 190 A.h.

The storage ring is divided up into 24 cells, each consisting of an arc section and a straight section. The arc sections contain the main magnet elements while the insertion devices are installed in the straight sections. 3 of the 24 straight sections are dedicated for injection, RF and diagnostics.

All 24 arc sections have been continuously under vacuum since installation was completed in April 2006 and have not been vented. Vacuum interventions have been made since then in 11 of the straight sections mainly for installation of new insertion devices, superconducting RF cavities, injection system elements and diagnostic elements. In general these interventions have been carried out in a similar way to the initial installation under a dry nitrogen purge system using clean, pre-baked components without an in-situ bakeout. We have had good results with this technique which involves a sequence of pumping, flushing and back-filling with nitrogen which we believe to more effective in

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removing traces of water from the system than a simple one-stage pump down. This is something we plan to investigate systematically to evaluate its effectiveness and to optimise the process.

Until recently there was only one superconducting RF cavity installed and the maximum stored current was limited to 170 mA with 125 mA during typical user beam sessions. A second similar RF cavity has now been installed which will enable the stored current to be increased to the design value of 300 mA in the near future. A third similar cavity will be installed later.

All pressure values reported in this paper are obtained by a simple un-weighted mean of all inverted magnetron gauge (IMG) readings in the relevant vacuum sections. The gauges are nominally calibrated for nitrogen; the values have not been corrected for gas composition, which residual gas analysis shows typically to be >90% hydrogen without beam and >80% hydrogen with beam. When this is taken into account, the true pressures will be approximately twice the values reported here.

2. Vacuum performance

2.1. Static pressure

Table 1 show the measured static (no beam) pressures in different storage ring sections after several weeks without beam, towards the end of a recent maintenance shutdown.

| Section                  | Static pressure (mbar) | Dynamic pressure 125 mA (mbar) |
|--------------------------|------------------------|---------------------------------|
| Entire storage ring      | $4.2 \times 10^{-10}$  | $7.9 \times 10^{-10}$           |
| All arc sections         | $2.1 \times 10^{-10}$  | $5.8 \times 10^{-10}$           |
| All machine straights   | $8.0 \times 10^{-10}$  | $1.1 \times 10^{-9}$            |
| Injection straight       | $1.6 \times 10^{-9}$   | $3.1 \times 10^{-9}$            |
| Diagnostic straight      | $5.8 \times 10^{-10}$  | $1.1 \times 10^{-9}$            |
| RF cavities              | $5.8 \times 10^{-10}$  | $1.6 \times 10^{-9}$            |
| Beamport absorbers       | $4.3 \times 10^{-10}$  | $2.0 \times 10^{-9}$            |

The highest pressure is in the injection straight which had very limited possibility for pre-baking components prior to installation. Due to the position of the gauges and wall cryo-pumping, the true pressure in the cold, superconducting RF cavities is likely to be much lower than the reported value. Beamport absorbers are water cooled copper photon absorbers fitted where no front end is installed.

2.2. Dynamic pressure

With 125 mA of stored beam at 190 A.h beam dose, the mean pressure in the storage ring rises to $7.9 \times 10^{-10}$ mbar (see table 1) due to photon stimulated desorption (PSD). The pressure rise is fairly uniform around the ring with no particular "hotspots".

Figure 1 shows the dynamic pressure in the storage ring as a function of beam dose ($D$). Each point in the plot was obtained from the slope of a least squares linear fit of mean storage ring pressure vs stored current. Where possible, data immediately following injection were discarded as the pressure takes some time to reach dynamic equilibrium following a sudden change in stored current.

Apart from the initial section below 0.01 A.h, the dynamic pressure follows a $D^{-0.7}$ dependence similar to that reported during conditioning of other storage rings.

From comparison with vacuum system simulations it should be possible to use the measured dynamic pressures at different positions in the storage ring to estimate PSD yields and to validate the simulations. This work is in progress.
2.3. Beam lifetime

Figure 1 also shows the current x lifetime product as a function of beam dose. As expected, the lifetime increases as beam conditioning progresses. The step change at 0.7 A.h is not vacuum related and is due to a beam re-alignment in the storage ring. The fall off in lifetime above 140 A.h is also thought to be unrelated to vacuum but to be due to operating the RF cavity at reduced voltage during the last machine run. The lifetime also falls slightly when the superconducting wiggler is energised.

The typical measured beam lifetime at 125 mA is around 20 hours. Work is currently in progress to estimate the relative contributions of gas lifetime and other effects such as Touschek lifetime and to relate the gas lifetime to the measured pressure and gas composition data. The target lifetime of a minimum of 10 hours at 300 mA (current x lifetime product 3000 mA.h) is close to being met, although at somewhat higher conditioning dose than the originally predicted 100 A.h.

2.4. Insertion devices

Eight insertion devices (IDs) are installed comprising six in-vacuum (in-vac) undulators, one out-of-vacuum (ex-vac) undulator (including a 4.9 m long NEG-coated aluminium vessel with 11 x 74 mm internal elliptical aperture) and one superconducting multipole wiggler (SCW). Their vacuum performance is summarized in table 2.

Table 2. Measured pressures in insertion device straights at 190 A.h beam dose

| Section                          | Static pressure (mbar) | Dynamic pressure 125 mA (mbar) |
|----------------------------------|------------------------|---------------------------------|
| In-vac undulator vessel          | 2.0 \times 10^{-10}    | 6.0 \times 10^{-10}             |
| In-vac undulator pumping station | 2.5 \times 10^{-10}    | 7.2 \times 10^{-10}             |
| Ex-vac undulator pumping station | 5.0 \times 10^{-10}    | 1.2 \times 10^{-9}              |
| SCW pumping station              | 8.5 \times 10^{-10}    | 2.8 \times 10^{-9}              |

For the in-vac undulator (ID03) both the pressure in the undulator vessel and in the downstream pumping station are given. For the ex-vac undulator (ID06) and the SCW (ID15) only the pressure in the downstream pumping station is given as it is not possible to measure the pressure in the device itself.

3. Vacuum protection system

The most important elements of the vacuum protection for the storage ring are:

- Two independent vacuum trip levels based on IMG readings; the first level (typically 10^{-7} mbar) dumps any stored beam via the hardware Machine Protection System while the second level (typically 10^{-6} mbar) closes the vacuum valves using PLC-based logic.
• A fast-closing vacuum valve in each front end [3] and in the Booster-to-Storage-Ring (BTS) transfer line, each interlocked to as many as 4 fast pressure sensors.
• 2 gate valves in each front end, 48 RF-shielded gate valves in the storage ring, 1 gate valve in each of the 48 front end / beamport absorber interfaces and 2 gate valves in the BTS transfer line. These are pneumatically operated and interlocked to IMG pressures and also to the presence of stored beam to protect them from synchrotron light damage.
• Approximately 1000 temperature sensors at critical positions such as photon absorbers, vacuum vessels and apertures. Some of these are connected into the machine protection beam trip system and some are displayed for information. All temperatures are archived regularly.
• Many other interlocks, for example each ion pump is interlocked to a local Pirani gauge to prevent it being turned on at atmosphere and each RGA is interlocked to a local IMG to prevent it being turned on above $10^{-4}$ mbar.

We have not had any serious vacuum incidents in the accelerators or beamlines yet so we cannot report on the effectiveness of these systems in protecting against a serious vacuum incident. We have experienced a few vacuum-related beam trips which have mainly been attributed to real (but not serious) vacuum outgassing events. The frequency of vacuum-related beam trips has been reducing as the vacuum conditioning progresses and as the vacuum protection logic has been refined.

4. Vacuum control and monitoring system
The EPICS-based vacuum control system is now fully operating and all vacuum parameters can be displayed, modified and archived as needed from graphical user interface screens.

One recent highlight is the completion of commissioning of the residual gas analyser (RGA) network. 122 RGAs on the Diamond accelerators and beamlines are linked to EPICS with live display and archiving of the most important partial pressures. Any RGA can also be operated remotely over the network for more detailed expert diagnosis of vacuum problems.

5. Operational issues
The vacuum system has proved to be very reliable in operation so far. Most vacuum interventions have been for installation of new equipment and only three major unplanned interventions had to be made:

• Replacement of the copper vacuum vessel liner of the superconducting multipole wiggler which had become distorted due to magnetic forces during a magnet quench.
• Replacement of a ceramic kicker vessel which had a damaged internal metal coating. The problem was identified from the larger temperature rise seen in this vessel compared with other similar installed vessels.
• Removal of one of the superconducting RF cavities which had developed a leak.

One interesting feature we have observed, as the dynamic pressure reduces with beam conditioning, is that IMGs in certain positions fail to read the pressure correctly with beam in the storage ring, possibly due to interference from stray or secondary electrons produced by the beam. Ways to overcome this, including fitting a permanent magnet filter on the gauge connecting tube, are being investigated.

References
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