Diamond Light Source Vacuum Systems: The First Seven Years of User Operations

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Topics

Overview of Diamond Vacuum Systems

What’s changed since Day 1

Operational performance

Some things which did not go according to plan

Some upgrades and future plans

... a slightly random walk of different topics ...
What is Diamond Light Source?

- The UK national synchrotron facility, 100 km from London
- Generates brilliant beams of light, from infra-red to hard X-rays, for a range of science applications
- 3rd generation light source making heavy use of insertion devices in straight sections (undulators and wigglers)
- Construction began in early 2003
- User operations began in January 2007 with 7 beamlines operational (Phase 1)
- April 2014 ≈22 beamlines operational (Phase 2)
- More beamline in construction and planned - increase to 32(33) beamlines over the next 4 years (Phase 3)
Diamond layout

3 GeV electron storage ring
562m circumference
<10^{-9} mbar

Booster synchrotron
100 MeV Linac
Front end
Beamline
Aerial view
Why ultra-high vacuum?

• Storage ring
  • $p < 10^{-9}$ mbar
  • Interactions between circulating electrons and residual gas molecules
    – Stored beam lifetime
    – Gas Bremsstrahlung radiation
  • Scales as $Z^2$ – minimise high $Z$ gases – $H_2 \Sigma Z^2=2$, $CO \Sigma Z^2=100$

• Beamlines
  • Hydrocarbon contamination of x-ray optics (mirrors, gratings, crystals)
  • Some sample environments require UHV
  • Gas phase absorption and scattering

• Residual gas
  • Hydrogen often predominant but not a problem – low $Z$, non-contaminating
  • Water and hydrocarbons need attention

• Electrons
  • Disappear after use!
  • Very low or zero activation
Main SR vacuum mechanical upgrades since initial build

- 8 of 72 girders replaced with specials
  - 1 x B22 IR beamline
  - 3 x I13 Double mini beta lattice
  - 2 x I09 Double mini beta lattice
  - 2 x I10 Helical undulators with polarisation switching
- 26 front ends installed (20 ID, 6 BM)
- 20 of 22 insertion device straights installed
  - 15 in-vac undulator (including 1 cryo)
  - 11 NEG coated vessel for ex-vac ID (up to 6m long)
  - 2 superconducting multipole wiggler
- Various vacuum improvements in and around the superconducting RF cavities
- Beam diagnostics relocation and additions
Main vacuum controls upgrades since initial build

(System based on EPICS)

- Many refinements to interlock system to reduce unwanted beam trips
- Permanent magnet filters fitted to prevent stray electrons affecting IMG gauges
- Some Piranis stop working in the presence of stored beam. Thought to be RF heating but not well understood. Pirani interlocks overridden
- Development of new fast valve control system
- Development of new fast mask add-on to the fast valve system
- Introduction of new ion pump controller MPC-e
- Introduction of new cold cathode / Pirani gauge controller 937b
- Introduction of new RGA controller MV2 and improved RGA integration with EPICS
Residual gas >90% H2 + remainder mainly CO

ca 400 A.h
### Operational reliability

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>User beam hours</td>
<td>3160</td>
<td>4092</td>
<td>4536</td>
<td>4753</td>
<td>4657</td>
<td>4656</td>
<td>4728</td>
</tr>
<tr>
<td>Uptime (%)</td>
<td>92.3</td>
<td>94.9</td>
<td>96.4</td>
<td>97.4</td>
<td>98.0</td>
<td>97.9</td>
<td>98.0</td>
</tr>
<tr>
<td>MTBF (h)</td>
<td>10.7</td>
<td>14.5</td>
<td>21.1</td>
<td>27.3</td>
<td>55.4</td>
<td>54.1</td>
<td>50.8</td>
</tr>
<tr>
<td>MTTR (h)</td>
<td>0.71</td>
<td>0.60</td>
<td>0.77</td>
<td>0.72</td>
<td>1.11</td>
<td>1.07</td>
<td>0.93</td>
</tr>
<tr>
<td>Total beam trips</td>
<td>297</td>
<td>282</td>
<td>215</td>
<td>174</td>
<td>84</td>
<td>86</td>
<td>93</td>
</tr>
<tr>
<td>Vacuum beam trips</td>
<td>26</td>
<td>22</td>
<td>15</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>SR RF beam trips</td>
<td>132</td>
<td>178</td>
<td>119</td>
<td>113</td>
<td>32</td>
<td>34</td>
<td>57</td>
</tr>
</tbody>
</table>

Target was 48h now 72h MTBF – so some work still to do
Big improvement in RF system from 2010 to 2011 partly attributable (probably) to improvements in vacuum environment in and around the superconducting cavities
Vacuum beam trips

• Beam-related pressure spikes in newly installed vessels
  – Initially caused quite frequent beam trips
  – Interlock system upgraded to require simultaneous events (gauge – gauge – ion pump) to trip beam
  – Large events can still trip the beam on pressure or cause partial beam loss / instability and trip on beam position interlock

• Equipment failures
  – Gauge controllers – various failure modes cause pressure interlock to drop and can trip beam
  – Plan to make interlock system more tolerant

• Beamline outgassing events (slits etc)
  – Close front end absorber rather than trip beam
  – Trade-off between beamline vacuum protection and reducing beam trips (fast mask system)
Some accelerator component failures

Titanium coating damage inside ceramic kicker vessel

Electrical insulation failure caused melted hole in septum vacuum vessel (x2)
Some beamline vacuum issues

Failed shutter bellows after a few hundred cycles – mechanical design error (multiple cases)

Broken window on beamline (x2)

Carbon deposition on x-ray optics

Pressure spikes from ferrofluidic vacuum seals
Synchrotron radiation heating damage

Melted LN2 pipe in monochromator due to undulator beam heating

Melted hole in fast closing vacuum valve titanium plate due to undulator beam
Kapton insulated wire problem

Material loved by beamline designers

Pressure spikes trip interlock system

Beam on only

RGA

Mass 69

CF$_3^+$

IR mirror and x-ray absorber in beamline B22
Kapton insulated wire problem

This Kapton insulated wire contains unexpected FEP binder which breaks down due to scattered x-rays.

Solution: remove Kapton insulated wire near strong x-ray beam absorber or scatterer.

Multiple occurrences in different front ends and beamlines.

CF$_3^+$ also seen with electron irradiation (5keV) in test system.

All Kapton insulated wires are not equal!!!
**Pressure gauge controllers**

<table>
<thead>
<tr>
<th><strong>937a</strong></th>
<th>OLD</th>
<th><strong>NEW</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Fixed EPROM enabled controller</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• 5 settable volt free interlocks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• 2 volt free interlocks factory set</td>
<td></td>
<td></td>
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<tr>
<td>• Up to 3 gauge boards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Faults with firmware and EPROMs in units had to be replaced</td>
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<td></td>
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</tbody>
</table>

**937b**

<table>
<thead>
<tr>
<th><strong>OLD</strong></th>
<th><strong>NEW</strong></th>
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</thead>
<tbody>
<tr>
<td>• Not 100% plug compatible</td>
<td></td>
</tr>
<tr>
<td>• Flash firmware in situ from PC</td>
<td></td>
</tr>
<tr>
<td>• 12 settable volt free interlocks</td>
<td></td>
</tr>
<tr>
<td>• 2 off fast switching interlocks on input amplifier of CC cards</td>
<td></td>
</tr>
<tr>
<td>• May install up to 3 gauge boards.</td>
<td></td>
</tr>
<tr>
<td>• Greater flexibility</td>
<td></td>
</tr>
<tr>
<td>• Major problems with errors in firmware versions and with the HV power supply of the CC boards. Issues are being corrected by supplier</td>
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</tbody>
</table>

**Poor control of firmware releases**

Faults likely to cause beam trips
MV+  
- Connects to server in PC via serial interface.
- 2 off amplifier settings for each multiplier setting.
- Runs RGA using “Process Eye” supplier Windows based software
- Currently issues with migrating from XP to Windows 7

MV2  
- Built in processor running Windows CE
- RGA server runs within unit
- Run RGA server directly from EPICS or Web page or Process Eye running client on windows PC
- Simple 1 off amplifier setting per multiplier setting.

12 key masses archived continuously
Useful for troubleshooting but need a lot of care and attention to keep them running
Ion pump controllers

**MPC-II**
- Firmware upgrades difficult
- Early units had poor tolerance to discharges in pumps and unreliable control of TSPs

**MPC-e**
- Firmware upgrades simple to perform
- Better tolerance to electrical noise
- Works better with TSPs

**Poor control of firmware releases**
- Ion pumps themselves relatively trouble free
Initially used VAT controller
Based on dedicated Pfeiffer IKR sensors
Works well but expensive and inflexible

Always requires signal from two sensors to trigger
No issues with false triggering

Migrated to in-house developed unit
Based on standard MKS IMG sensors
Saves on duplication of gauging and cost of unit
More flexible integration into Diamond MPS and EPICS
Manual right-angle all-metal valves

- DN63
  - A lot of problems with leaking VAT Series 54 valves
  - Seem to be sensitive to particulates
  - Following tests, changed to using VG Scienta valves – (Special ZCR60R with silver plated copper sealing pad and 316LN flanges) – many fewer problems
  - Fit additional valve in series in case of critical leak
- DN40
  - Still using VAT Series 54 valves
  - No major problems
- Routinely fit pump out blank / dust cover to all R/A valves
RF gate valves

• Valves (VAT Series 47) relatively problem-free
  – Valve-to-valve variation in body temperature and heating mechanism not well understood ($\Delta T$ range from 2 to 18°C at 250 mA)
  – May be related to adjacent flange joints or valve itself
  – May be related to some observed distortion of flexible RF fingers
  – Hot valves could be limiting for increase from 300 to 500 mA

• Air solenoid valves
  – Regular failures – degradation of some internal seals
  – Does not normally cause beam trip but if valve closes for some reason it cannot be re-opened
  – Cause unknown – radiation?
  – Just completed replacement of ca 150 units in storage ring
  – Will monitor failures and consider replacing every 3 to 5 years

• Air pressure switch failures
  – A few failures
  – Can lead to beam trips via MPS
RF cavities

• 3 superconducting 500 MHz (Cornell type) cavities
  – only 2 installed at any one time to keep one spare
  – 4\textsuperscript{th} cavity due for delivery soon
  – Various swaps of the 3 cavities carried out for operational reasons
  – 3\textsuperscript{rd} cavity should be installed distant from the other 2 cavities in case of a vacuum incident

• Vacuum and operating improvements 2010/2011 – to reduce and control cryosorbed gases in the cavities and waveguides:
  – Additional NEG pumps installed
  – Original make up pieces replaced with 450°C vacuum baked vessels
  – Weekly TSP firing
  – Regular high power pulsed RF conditioning to dislodge adsorbed gases in the waveguide and cavities
  – Regular partial warm up to around 50K to desorb cryosorbed gases (H\textsubscript{2}, CO): No obvious diagnostic to say when this is needed
  – Various changes to RF power feed and control systems

• Special slow pumping and venting procedures with filtered dry nitrogen in and around cavities - particulates
Towards 500 mA

• Currently operating at 300 mA which was the design spec for Diamond
• 350 mA operation was tried and found unreliable with 2 RF cavities operating near their power limits
• Longer term aspiration to increase to 500 mA
• 500 mA may produce too much RF heating (scales as $I^2$) in BPM buttons and RF gate valves etc unless bunches lengthened
• Likely to require:
  – 3 operating RF cavities (4th cavity as spare)
  – Bunch lengthening to reduce beam RF heating (harmonic cavity) – current bunch length around 4 mm – 13 ps
  – Upgrades to beamlines and detectors to take advantage of increased flux
Some beamline challenges

- I14 long beamline (similar to I13)
- I23 end station and detector (in assembly)
- B21 (HATSAXS) automated camera tube exchange system
- I21 may require 8m long NEG coated ID vessel
- X-ray optics in the front end space, e.g. B22, B23, B24, B07 with infrequent, limited access
- Complex end-stations operated by inexperienced users - automation
- Complex beamline controls and interlocks
- Trade off of machine trips and beamline vacuum protection
- Inappropriate materials, e.g. Kapton insulated wire with fluorocarbon binder in high radiation areas
I23 in-vacuum end station

- Pressure < $1 \times 10^{-6}$ mbar with all items fitted
- Vacuum vessel ca $1.5 \times 1 \times 1.5$ m
- Collimation system
- Goniometer
- Tomography camera
- Fluorescence detector
- Diffraction detector
B21 (HATSAXS) camera tube exchange system

High throughput - to change camera focal length
Automatic exchange and pump down ($\approx 10^{-2}$ mbar) of 400 $\phi$ tubes up to 2m long
Beamline I13

- Complex beamline with two main branches (CO and IM)
- External vacuum duct
  - Two 150m long x-ray beam pipes 100 to 200 mm diameter
  - Windowless
  - Pumped from ends only (except during installation)
  - Differential pumping to achieve UHV $\sim5 \times 10^{-9}$ mbar at both ends
- Exposed to ambient temperature variation = outgassing rate variation
- In-situ baked
- New design fast-closing copper mask to protect normal fast-closing valve from SR to give more vacuum protection options
- Beamline I14 will be similar
Future upgrades and challenges

• Increasing expectations for machine reliability – target > 72h MTBF
• Beamline protection vs overall machine reliability
• Maintain and improve supplier vacuum QA for beamlines and small quantities of vessels
• One-offs of complex vessels for spares and upgrades: manufacturers maybe unable or unwilling
• Obsolescence and long-term support for equipment and spares
• DDBA upgrade
• Increase beam current to 500 mA ????
• Vacuum beamline for PSD measurements / NEG ????
• Longer term Diamond II – low emittance lattice upgrade ????
Summary

• Diamond has a large and complex set of vacuum systems
• It is operating reliably to specification ($<10^{-9}$ mbar in the storage ring). The main residual gas is hydrogen
• Many small and medium size upgrades have been installed over the past 7 years
• A number of vacuum challenges had to be solved along the way
• The journey is not over yet and there are more challenges to come
Thanks to ....

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