DIAMOND LIGHT SOURCE:
A 10-YEAR VIEW OF THE PAST AND VISION OF THE FUTURE

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Abstract

Diamond Light Source has been in regular operation for users for 10 years and so it is an appropriate moment to review the successes and challenges of the past, and also consider the vision for the next 10 years.

INTRODUCTION

The case for a 3rd generation synchrotron light source in the UK to replace the Synchrotron Radiation Source (SRS) at Daresbury emerged in the 1990's [1]. Following various iterations a design finally emerged for a medium-energy 3 GeV machine with 24 cells in order to provide low emittance with a high capacity for insertion devices [2]. Table 1 summarises the main parameters of the final design of the Diamond storage ring [3].

Table 1: Main Parameters of the Diamond Storage Ring

Parameter	Value
Circumference	561.6 m
Energy	3 GeV
Lattice	24 cell DBA
Natural emittance	2.7 nm rad
Long straights (quad-quad)	6 x 8.3 m
Standard straights (quad-quad)	18 x 5.3 m

Diamond Light Source Ltd. was created under a Joint Venture Agreement between the UK Government and the Wellcome Trust in March 2002 to build and operate the Diamond facility. Ground breaking for the enabling works took place in March 2003 and less than 4-years later in January 2007 Diamond had its first external "expert" users on 4 beamlines and was operating at 125 mA. By the end of the scheduled optimisation phase in Sep. 2007 six of the seven Phase I beamlines had received external users and regular users were accepted from Oct. '07 (the seventh beamline received users in Dec. '07). Significant changes to the machine have been made since then, as detailed below.

THE FIRST TEN YEARS: 2007-2016

Operating Performance

The performance of the Diamond storage ring has been dominated for many years by that of the RF system – in particular the superconducting cavities. Figure 1 shows the evolution of the maximum operating current and also which cavities were installed as a function of time. A failure of cavity #3 during commissioning in June 2006 led to start-up with a single cavity in 2007 and a limited current of 125 mA. Cavity #2A was subsequently installed which allowed the beam current to be slowly increased to 250 mA. Cavity #2A failed in Dec. 2010, but couldn't be replaced immediately by the repaired cavity #3 which caused a further set-back in beam current. 300 mA was first achievable in Jan. 2012 but the current had to be restricted to 250 mA until April due to a beamline issue. Further cavity failures in Sep. 2014 and Jul. 2015 also impacted on beam current – as well as reliability.

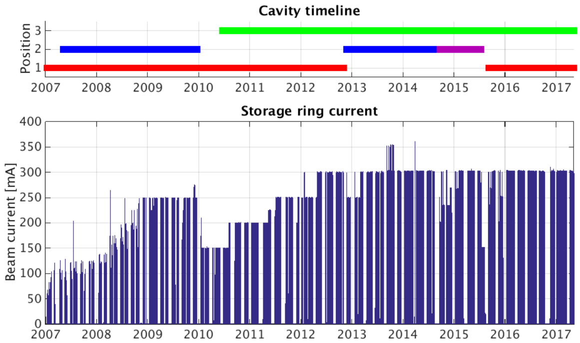

Figure 1: Beam current evolution (lower) and graphic showing which of the three superconducting cavity locations were occupied (upper); colours indicate different physical cavities.

Reliability has also been heavily influenced by the RF system, both cavity trips as well as problems with the IOT amplifiers, and a lot of effort has been spent in learning how to manage these [4]. Other significant sources of beam trips initially were water cooling systems and also spurious trips due to the global interlock system. Figure 2 shows the evolution of MTBF and uptime by reporting year (March-April).

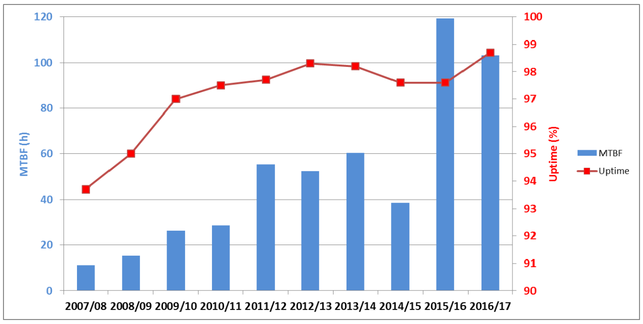

Figure 2: Evolution of mean time between failures (MTBF) and uptime for the Diamond storage ring.

The initial goal of 48h MTBF was achieved in 2011/12 and the subsequent target of exceeding 72h has been

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achieved in the last two years. Operational issues are discussed in more detail in [5].

Feedback Systems

Fast orbit feedback has been in regular operation since July 2007 providing sub-µm stability in both planes and insensitivity to ID gap changes. It provides some innovative features compared to traditional PI controllers [6].

Transverse Multibunch Feedback has been in regular operation since 2008 [7] and while not strictly required for stabilisation at 300 mA it provides resilience against ion beam instabilities present after vacuum interventions. The system has also been extended to provide permanent betatron tune measurements which in turn allowed the implementation of a tune feedback [8].

A reduction in coupling, resulting in a reduction of vertical emittance from 27pm to 8pm, was established as the normal operating mode in Mar. 2013. A feedback system was introduced in order to maintain constant vertical emittance [9]. A summary of all feedback and feed-forward schemes is given in [10].

Top-Up Operation

Following a period of preparation [11] which included detailed safety simulations [12], top-up operation was introduced on a regular basis in user mode in Oct. 2008. The basis of the operation has essentially remained the same since then: injection takes place regularly at 10 minute intervals. Since then top-up has also been extended to other operating modes such as low-alpha.

Machine Changes

Significant changes to the optics of two long straight sections (I13 and I09) were made in Aug. 2010 and Mar. 2011 to introduce two local minima in the vertical beta function, in order to accommodate two small gap IDs, as well as horizontally focusing optics. This involved swapping out the two girders on either side of the relevant ID with modified ones to which additional quadrupoles had been added, as well as installing an additional mini-girder at the centre of the straight with a new quadrupole doublet [13]. An additional smaller optics change was made in another long straight to reduce the vertical beta at the centre from its standard value of 5.8m to 3.4m, while keeping the tune constant.

A further significant change, involving two more girder swaps, was made in Aug. 2011 to prepare for the installation of a series of five “kicker” magnets in the I10 straight section in order to provide polarization switching on the I10 beamline at 10 Hz repetition rate. The kicker magnets themselves were installed in Jan. 2012 and polarization switching was commissioned shortly afterwards. A paper reviewing the method that was implemented to correct the residual 10 Hz disturbance on the electron beam and make it transparent to other users is in preparation [14].

Double-Double Bend Achromat

The concept of converting individual cells of the double bend achromat (DBA) lattice into a 4-bend, or “double-double bend achromat” (DDBA) with a new ID straight section in the middle was motivated by the fact that all straights were either occupied with IDs or allocated to future beamlines and there was a particular need to accommodate a further beamline with a standard in-vacuum undulator as its source [15]. The conversion of the cell required two completely new girders to be assembled with new narrow gap vacuum vessels and new narrow aperture dipole, quadrupole and sextupole magnets etc. [16]. In order to minimise the shutdown time required for installing the new cell to 8 weeks, an elaborate sequence of cabling activities was undertaken, starting more than two years in advance of the shutdown [17]. The actual installation and re-commissioning took place between Oct. 7th and Dec. 5th 2016 and regular operation at 300 mA with top-up resumed according to plan on Dec. 6th. Further details are given in several other papers at this Conference [18-21].

Insertion Devices

All 7 Phase-I IDs were installed in Aug. 2007 before the start of 3 GeV commissioning; these included 5 in-vacuum undulators, an APPLE-II undulator and a 3.5 T superconducting multipole wiggler. Initial operation of in-vacuum undulators was at a minimum gap of 7 mm, which was later decreased to 5 mm in 2008. Progressive installation of Phase-II and Phase-III beamline IDs followed, the last in Oct. 2015 left no further space for IDs, until completion of the DDBA project (see above). The total complement of ID modules is currently as follows; further details are given in [22].

- 16 in-vacuum undulators operating at 5 mm minimum gap, including one cryogenic permanent magnet undulator (CPMU),
- 8 APPLE-II devices, three of which 4.5-5m long,
- 1 short ex-vacuum undulator,
- 2 permanent magnet multipole wigglers,
- 2 superconducting multipole wigglers (3.5T, 4.2T).

THE NEXT TEN YEARS: 2017-2026

Vision

The development of a 10-year vision for Diamond, covering both scientific and technical aspects, was launched in Feb. 2014 and concluded in Oct. 2015 [23]. As regards the machine, the main areas highlighted for development were:

- Improved resilience and reliability, especially in view of problems that had been experienced with the RF system,
- Improved electron and photon beam stability,
- Improved brightness through the development of new insertion devices,
- Preparation for a possible major upgrade of the machine, Diamond-II.

RF and Related Upgrades

Normal conducting cavities. As shown above, the reliability of Diamond has been significantly impacted by

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the performance of the superconducting cavities and the IOT amplifiers. Failures of superconducting cavities have resulted in significant downtime as well as reduced beam current and reliability for a period after the removal and replacement of the failed cavities. To provide greater operating margin and hence greater resilience against any future difficulties with the superconducting cavities, it has been decided to install two additional normal conducting cavities of the HOM-damped design similar to those currently in use at ALBA and BESSY-II. The cavities have been delivered and are due for installation in Aug. and Nov. 2017 [24]. The installation of further normal conducting cavities will also be considered, based on experience with the first systems.

IOTs and SSAs. The extra operating margin when both normal and superconducting cavities are functioning will also provide some extra resilience against failures in the RF power sources. By operating the four inductive output tubes (IOTs), whose outputs are combined to feed each superconducting cavity, at lower power it will be possible to switch off the HV feed to any individual IOT and so survive an IOT trip without loss of beam [24].

In the longer term, the IOT amplifiers will most likely be replaced with solid-state amplifiers (SSAs) which have much greater reliability. The high cost has however deterred us from going in this direction at this stage. Two smaller SSAs have however recently been ordered, an 80 kW system to power the RF Test Facility and a 60 kW system to power a second booster RF cavity.

DLLRF. New low-level RF systems were also required for the new systems and the opportunity has been taken to develop a modern digital system which will also provide greater longitudinal stability. A digital low-level RF system (DLLRF) has been developed in collaboration with ALBA. A prototype system has recently been successfully tested on the booster and series production is underway to deploy it on the two existing superconducting cavities and two new normal conducting cavities [25].

LMBF. In anticipation of the installation of the normal conducting cavities, and in order to maintain beam stability under all operating conditions, a Longitudinal Multibunch Feedback (LMBF) system has recently been designed, installed and commissioned [26].

Electron and Photon Beam Stability

Even with the reduction in vertical emittance to 8 pm, the current rms vertical orbit stability is still only 2% of rms beam size when integrated up to 100 Hz, however there are sources of vibration at higher frequencies that increase this to 10% of beam size up to 1 kHz. The steadily increasing speed of detectors on beamlines means that this should be improved. A program has therefore begun to investigate the sources of vibration at higher frequencies - believed to be dominated by the water cooling system - and to try to reduce them. We are also investigating dedicated high bandwidth correction on particularly sensitive beamlines.

While the current disturbance to the stored beam during top-up is acceptable, it is envisaged that this may well become important in the future and so we are investigating ways of reducing this, for example using the nonlinear kicker scheme [27].

Insertion Device Upgrades

The desire for increased flux on a number of beamlines that exploit high photon energies is driving the development of new higher performance IDs [22]. A new design of CPMU based on PrFeB magnetic material and operating at 77K is currently under construction. The first two devices are due for installation in March 2018 and June 2018, replacing standard in-vacuum devices. Two further CPMUs have also recently been approved for installation in late 2018/early 2019. Superconducting undulators for the beamlines that require the highest photon energies (25-40 keV) are also being considered.

Diamond-II

When Diamond became operational in 2007 it had one of the lowest emittances of any 3rd generation light source. That position is however being eroded as new machines and upgrades start to come on line. The Vision document [23] recognised that for Diamond to remain competitive in the future, plans must be made for a major upgrade of the lattice. Accordingly an outline design and science case for Diamond-II was presented to the Diamond Science Advisory Committee in April 2016 and received a positive endorsement. The Board of Directors subsequently approved further study which will lead to a Conceptual Design Report. The lattice currently under study is a “Double-Triple Bend Achromat” (DTBA) [28]; this is based on the ESRF-EBS hybrid 7BA lattice and combines the benefit of low emittance (~ 120 pm) with the extra capacity for IDs provided by the central straight section, as in the DDBA cell.

“Missing sextupole” scheme

In order to accommodate a further beamline based on an insertion device source rather than a bending magnet, and to avoid the negative impact of installing a second DDBA cell, a compromise scheme has been developed to remove one of the chromatic sextupoles in the DBA arc, which leaves enough space for a 10-pole wiggler to be installed [29]. An outline design of the mini-wiggler has been completed [22] and fabrication of the required new vacuum vessels is underway. Installation by means of a girder-swap will take place in 2018.

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