THE DIAMOND CONTROL SYSTEM: FIVE YEARS OF OPERATIONS

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Abstract

Commissioning of the Diamond Light Source accelerators began in the 2005, with routine operation of the storage ring commencing in 2006, and photon beamline operation in January 2007. Since then, the Diamond control system has provided a single interface and abstraction to (nearly) all the equipment required to operate the accelerators and beamlines. It now supports the three accelerators and a suite of twenty photon beamlines and experiment stations. This paper presents an analysis of the operation of the control system and further considers the developments that have taken place in the light of operational experience over this period.

INTRODUCTION

Diamond Light Source [1], is a third-generation 3 GeV synchrotron light source based on a 24-cell double-bend achromatic lattice of 561m circumference. The photon output is optimised for high brightness from undulators and high flux from multi-pole wigglers.

Storage Ring (SR) commissioning was completed in two phases during 2006. An initial phase of commissioning, to establish accumulated beam at 700 MeV in the SR, took place during April and May 2006. This was followed by installation of the insertion devices for the first eight beamlines and a second phase of commissioning to establish operational conditions and undertake photon beamline commissioning. Routine user operation for the first seven photon beamlines began in January 2007.

Since January 2007 there has been an aggressive programming of photon beamline design, installation and commissioning, such that as of September 2011 there are twenty beamlines in operation, four beamlines in advanced construction or commissioning, and eight in various stages of design. During this period there have also been a number of developments of the accelerators to improve the performance and operational reliability. The operational photon beamlines have been developed with increased automation of samples and of data analysis, and the use of new detectors.

All of the above developments have required ongoing development and support from the control system. In addition, the control system has been managed to improve reliability and to prevent the onset of obsolescence.

RECAP ON THE DIAMOND CONTROL SYSTEM

The Diamond Control System [2] uses the EPICS toolkit [3] and provides a high degree of integration of the underlying technical systems. These include all power converters, most diagnostics, vacuum systems, the machine protection system, insertion devices, RF amplifiers, girder alignment, front-ends, photon beamlines, experiment stations, instrumentation and detectors.

Most of this equipment is interfaced through a range of generic VME I/O based on VME IP carriers, IP modules, transition cards and plant interface modules. For motion control, the OMS VME58 is used for straightforward applications; however, for synchronous control, the Delta Tau PMAC controller is used. Programmable Logic Controllers (PLCs) from Omron are used for interlocking and control, e.g. for vacuum valves, whilst for high-end process control applications, such as the Linac, the RF cavities and the cryo-plant controls, the Siemens S7 series of PLCs are used. The control system interfaces to the accelerator technical systems at 32 control and instrumentation areas (CIAs) and to photon beamlines at one or two CIA(s) for each beamline. The CIAs are air-conditioned rooms that maintain a clean and temperature-stabilised environment for the instrumentation.

A fibre optic infrastructure is installed from each of the CIAs back to the Control System Computer Room and from there to the Control Room. The fibres provide two computer networks, a control system network and a secondary computer network, and are also used for the timing systems, for the Machine Protection System and for the beam position feedback system.

A global Machine Protection System (MPS) [4] manages global equipment protection for vacuum vessels and series-connected magnets (SR dipoles, booster dipoles and booster quadrupoles). Whilst water and temperature are managed using PLC-based solutions local to each cell, some of the global interlocks, notably mis-steered beam, require a fast response and are therefore managed by bespoke MPS modules. The timing system uses a central event generator, with receiver modules located in each EPICS IOC.

Development and operational client platforms for the control system are PCs running RedHat Enterprise Linux.

Diamond has standardised on a combination of EPICS and GDA [5] for the control of photon beamlines, experimental stations and detectors. EPICS provides the low-level interface to the hardware and user interface functionality for engineering type operations, whilst GDA provides the science-based interface for the station scientists and visiting users of Diamond. The exception to this is where commercial instrumentation forms the basis of the experimental station.

CONTROL SYSTEM RELIABILITY

From day one of operation of Diamond, every beam loss has been recorded and analysed, along with nonbeam-loss faults, to understand failures. During the period 2007 to 2011 the number of operating hours per year has increased from 3048 hrs to 4848 hrs and the MTBF for the year has increased from 10 hrs to 53 hrs. Over this period, the number of beam loss faults caused by the control system (software, hardware and machine protection system induced) has fallen, as shown in Figure 1.

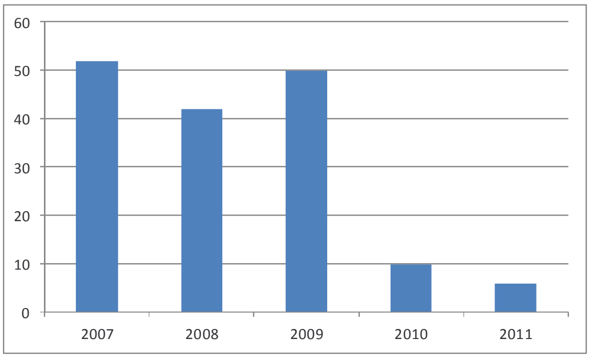

Figure 1: Number of control system faults by year to dump stored beam. For 2011, only 3648 hours have been operated out of 4848 scheduled hours.

The control system faults in 2007 were caused by a series of MPS faults related to the MPS logic for front ends, enabling beamline faults to propagate through the front ends and so causing the electron beam to be dumped. The requirements for the protection were reviewed and new logic applied to minimise these trips. This highlighted the need to take input from operations into account in the hazard analysis and assessment process.

In 2008 the faults were dominated by a series of faults in the global MPS system. These were difficult to diagnose as the beam loss causes all electron beam position monitors (BPMs) to indicate an orbit excursion interlock, within the sample time of the clock latching on the first interlock. The cause of the MPS fault was diagnosed to be a failure of optical transmitters and insufficient optical budget. In the first place the local MPS module transmitters were modified, and subsequently the global MPS module was redesigned to provide a post mortem capability. This problem highlighted the difficulties in diagnosing faults which are effectively in a feedback loop with the beam system and are beam critical.

In 2009 the faults were dominated by a failure of the Fast Orbit Feedback (FOFB), which despite traps in the software to shutdown the FOFB gracefully, still dumped the beam. It was again an intermittent fault and was due to a fault on the VME back plane on the bus grant acknowledge chain in one of the 24 VME crate controllers used for orbit feedback (possibly as a result of a tin whisker). This was again difficult to diagnose as it was intermittent and in the feedback so that it dumped the electron beam.

Whilst the underlying EPICS base software is very stable and the large deployed base quickly highlights any significant problems in new releases, each control system also includes many in-house-developed components (device drivers, database and configuration). Work has been performed on a number of tools to automate the building of EPICS databases [6] thereby minimising configuration errors, and on building unit tests for all in-house support modules. However, so far the unit tests have only been developed for a fraction of the total number of modules used.

MAJOR DEVELOPMENTS SINCE FIRST OPERATIONS

Since first operation, Diamond has installed fifteen photon beamlines, experimental stations and associated front ends. These have required in-vacuum, ex-vacuum, and cryo-cooled permanent-magnet insertion devices and two superconducting multi-pole wigglers. These have required two significant lattice modifications [7] for routine operation, adding additional quadrupoles to the SR, and a new lattice tuning for low-alpha operation to deliver electron bunch lengths of a few picoseconds. All of these have been supported by the control system. The following presents some key developments of the accelerator and beamlines involving the control system.

Control System

The machine control system was predominantly deployed with EPICS 3.13.9, (3.14.6 for Libera and soft simulations) as this was the stable version of EPICS in 2003 and so provided a stable platform for in-house work and for external suppliers delivering turn-key systems. The beamline control systems which started in development in 2005 adopted EPICS version 3.14.8.2. During the period 2008 to 2011, the machine control system was upgraded to 3.14.8.2. The difference in process and environment meant that the changes were involved and so required considerable testing. All the control systems are now in the process of being upgraded to EPICS version 3.14.11, and the policy is to try and keep all systems on a common version of EPICS base, core components and modules.

All development and operational client systems are Linux-based, whilst servers predominantly run under Linux or VxWorks, with a few Windows systems where only Windows drivers are available for a given piece of hardware. The version of Linux has been steadily upgraded such that it is currently Enterprise Linux 5, with a move to Enterprise 6 and 64 bit platforms in progress. In order to ensure quality of deployment, all applications are built on a build- and deployment-server, thereby ensuring consistency of the tool chain for the build of all operational systems.

Fast Orbit Feed Back

Diamond commenced operation running a client application to correct the orbit manually, after injection, then once per second during stored beam. This addressed issues from long term drift but did not suppress a range of disturbance induced from changing ID gap or from the environment. During 2007 the Diamond FOFB [8] was commissioned. It takes the data, at a 10 kHz update rate, from the 172 electron BPMs to 24 VME processor cards, which carry out the feedback processing to update the 344 corrector PSUs. It uses a low-latency high-bandwidth data path which is realised by connecting the Libera units and the computation nodes using the high-speed serial interconnections available on the Xilinx FPGAs. The interconnection is realised over a fibre optic link using the Diamond Communication Controller designed and implemented in VHDL. It provides excellent rejection of disturbances from ID scanning and environmental effects up to ~100Hz.

The data path further feeds an on-line spectral analysis application, and since 2010 this data is being recorded in a short-term archiver [9], storing the most recent three days of data to enable subsequent analysis of reported disturbances. Measurements of the forward and reflected powers and phases into each of the RF cavities have also been included by using the Libera electronics as RF power meters, and from that data, disturbances originating from the RF amplifiers were identified. Current work has included the design of an interface from the communication network to photon BPMs, to incorporate BPM data into the fast archive.

Whilst FOFB achieves the desired electron beam stability of better than 10% in beam dimensions, it is foreseen that improvements in this performance are likely to be required in the future. In preparation for this, the booster synchrotron is being operated as a storage ring at 100 MeV to develop and test new control algorithms for improved FOFB operation on the SR [10].

Top-up Operation

The initial design of Diamond made provision for top-up operation in the accelerator technical systems including the control system and Personnel Safety System (PSS). As part of the implementation of top-up [11], a hazard analysis was undertaken to define a safe operating regime. This defined limits on the integrated radiation losses and transfer efficiencies, and PSS logic for injection with shutters open, such that excursions outside these constraints would cause the electron beam to be dumped by the PSS. Critical parameters must stay within the safe operating window to avoid unnecessary beam dumps and ensure reliable operation. When a problem develops, it must therefore be detected before the PSS dumps the beam, causing machine operation to drop back to decay mode and so preventing beam loss. This supervision of top-up is managed by a client application implemented in Python and Qt which ensures that these requirements are met. It further generates and compiles statistics on the operation of the technical systems required, e.g. transfer efficiencies through each of the accelerators. These are produced for the last shot, the last 10 shots, the last hour, the last six hours and the last 24 hours and so give visibility to developing problems.

Top-up operation also required the provision of additional timing signals to each of the experimental stations, as both hardware signals and EPICS PVs, to gate data acquisition during the injection when the photon beam is disturbed by the effect of the injection kickers on the stored beam.

Archiving

Diamond has tried to archive as much information as possible about the environment, accelerators and beamlines. This is valuable in diagnosing beam losses and also in understanding and characterising long-term behaviour. By 2010 there were 12.5 TB of data on line, and the system was reaching the storage capacity; further, the storage rate was approaching the limits of the hardware, and the retrieval time had become unacceptable for both very wide (in terms of number of process variables) queries and for very deep (going back in time) queries. Despite segregation of indices by technical area, the 2 GB index limit was being reached. To address these problems, new hardware consisting of 36 TB of disk in a RAID 5 configuration has been installed. The 2 GB index limit has been eliminated from the code by moving from 32-bit file addressing to 64-bit, allowing a single master index to be implemented. The XMLRPC query interface has been extended to return structured arrays of data in one query. However, it is recognised that this solution is still close to what is achievable in terms of performance from the current architecture [12]. Increases in the amount of data archived or further improvements in retrieval times will require a new storage architecture.

Motion Control

Motion is realised through a variety of motion controllers which all use the EPICS Motor record to give a common interface. As part of this we have developed a system for co-ordinated motion over multiple axes [13]. Traditionally a sample has been scanned in a stop-start way, with acceleration time limiting the rate of acquisition. To address this, trajectory scanning has been developed, whereby complex motion is pre-programmed in to the motion controller, and a hardware trigger is used to take the data on the fly. The result has been a reduction in the time taken by a data scan for EXAFS from 50 minutes to 60 seconds [14].

Video Cameras

Support for video cameras was initially standardised on a range of cameras using the Firewire interface. These were interfaced with PMC Firewire interfaces located on VME processor boards and a commercial, (binary only) Firewire stack running under VxWorks. With limited numbers of cameras per bus and limited bus length these worked reasonably reliably, but the interface failed to support the specified maximum number of cameras per bus, and so it was migrated to use PCs and Linux. Again this failed to support reliably multiple cameras per bus.

Only on detailed investigation did it become clear that the Firewire stacks under both VxWorks and Linux were not full implementations of the standard. The most complete implementation tested was under that running under Windows XP. With Firewire declining in popularity, cameras are now being interfaced using Ethernet and the GigE protocol [15].

Excalibur Detector

A 2D position-sensitive detector is currently being developed for a range of imaging experiments. It is based on Medipix3 device, a 256 x 256 pixel photon-counting detector. The hardware to interface an array of these devices is being developed jointly with STFC [16]. The detector control, calibration and readout will use EPICS and the EPICS area detector module.

Transverse Multibunch Feedback (TMBF)

To damp coupled-bunch instabilities up to 250 MHz, a TMBF system was developed [17]. It consists of a detector in the form of a set of pick-up buttons, an in-house-developed RF front end, a commercial digital FPGA- based feedback electronic module called Libera Bunch-By-Bunch from Instrumentation Technologies, and stripline kickers. The FPGA functionality and the EPICS interface were developed in house. It provides good suppression of horizontal and vertical instabilities at 250mA beam currents with zero chromaticity, together with a range of operational diagnostic functionalities including continuous measurements of the betatron tune and chromaticity

Future Interface Standards

With a third phase of ten photon beamlines approved in 2010 it was considered timely to review the choice of control system interface platform. A decision was taken to move away from VME and to use network-attached I/O for all new beamlines and photon front ends. The resulting solution uses Ethernet-attached motion controllers, PLCs, cameras and serial devices through terminal servers, and ADCs, DACs and Digital I/O through Ethernet and the Ethercat protocol [18]. The IOC servers are 1U PCs running Linux with a real-time extension, where required.

CONCLUSION

The Diamond control system has met its initial objectives and gone beyond them, particularly in the control of experiment stations, and detectors. The overall contribution to beam losses has been at an acceptable level and early issues contributing to unreliability have been identified and addressed. Nevertheless, control system reliability is an area that continues to receive attention.

However, there remain areas for further improvement, including documentation of the installed system and in provision of unit tests for all mo dules. Both of these activities are limited by the available effort and priority. The latter is likely to be of significant value when a major change in the EPICS base software components is made.

Looking to the immediate future, most of the control system hardware is now six years old. Whilst it is not showing signs of increased failure rates, a number of hardware systems have been subject to end-of-life notifications by manufacturers. In all the cases to date, this obsolescence has been readily managed. Nevertheless, all areas need to be continually assessed such that the risk level from obsolescence presented to the overall project is limited to an acceptable level..

The main EPICS client applications (EDM, Alarm handler) are X11- and Motif-based, and somewhat dated, and so a move away from these applications is now being considered.

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