

MOTION CONTROL SYSTEMS FOR INSERTION DEVICES IN DIAMOND-II

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Abstract

Diamond Light Source has been operating since 2007, and currently has installed 26 motion-controlled insertion devices that produce synchrotron light for the majority of the 36 beamlines in operation. The Diamond-II upgrade will reduce the emittance, increase the energy of the electron beam, increase the number of straights available, and includes the delivery of three flagship beamlines. As part of delivering Diamond-II we plan to build and procure 12 new insertion devices of which 10 will be motion-controlled using in-house designed and built control systems. We also plan to upgrade three control systems to manage obsolescence and enable software upgrades. This paper describes the various generations of motion control systems present, and outlines the upgrade plans, controls challenges, and special requirements.

INTRODUCTION

Diamond Light Source is the UK's national synchrotron science facility, located at the Harwell Science and Innovation Campus in Oxfordshire [1]. The *Diamond-II* upgrade has been in development for several years and reached a milestone in 2023 when its funding was approved by the government. The upgrade project will modify the accelerator lattice to offer brighter beams and increase capacity using a 6-bend-achromat design that provides 24 new "mid-straight" sections [2].

Diamond has 29 insertion devices in operation [3,4] as shown in Table 1. The column *phase* indicates a chronology of the various ID control system generations.

As an illustration of the capacity upgrade the tables below show 8 systems planned to be removed (entries not in bold in Table 1) and 12 are to be installed (Table 2).

Further discussion in this paper will ignore the I12 and I15 superconducting multi-pole wigglers (SCMPW) and the K11 fixed-gap wiggler that don't require motion control.

PHASE I IDS

The motion control system for these insertion devices consists of the following hardware [5]:

- VME based EPICS IOC.
- OMS58 motion controller card.
- Parker Hannifin Compax servo drives, motors, brakes and resolvers.

Table 1: IDs in Operation as of Aug. 2025

No	Beamline	ID type	Phase	Notes
1	I02	IVU	Phase I	a
2	I06-A	Apple-II		
3	I11	IVU		
4	I15	SCMPW		b
5	I16	IVU		
6	I18	IVU		
7	I12	SCMPW	Phase II	b
8	I06-B	Apple-II		
9	I10-B	Apple-II		
10	I10-A	Apple-II		
11	I07	CPMU		
12	I22	IVU		
13	I09	IVU		
14	J09	Apple-II		
15	I13	IVU		
16	J13	IVU		
17	I19	IVU		
18	I20	Wiggler		
19	K11	Wiggler	Phase III	b
20	I05	Apple-II		
21	I08	Apple-II		
22	I14	IVU		
23	I21	Apple-II		
24	I23	IVU		
25	J02	CPMU	Upgrade program	
26	I03	CPMU		
27	I04	CPMU		
28	J04	HPMU		
29	I24	CPMU		

Notes: (a) upgraded controls, (b) no motion control, **bold** indicates ID staying for Diamond-II

- TR Electronics linear absolute 0.1 μm resolution encoders and interfaces.
- Omron protection PLC.
- Applied Geomechanics tilt sensors.

The OMS58 motor controller cannot read absolute encoders, therefore the system uses a dedicated *Active PLC* module capable to read the SSI signals together with a mechanism to load the encoder positions before enabling motion.

Figure 1 shows an example Phase-I ID.

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Table 2: List of Diamond-II IDs

No	Beamline	ID type	Notes
1	K02	CPMU-6	a
2	I05	Apple-K	a
3	I06-A	EMPHU	a
4	I17 CSXID	Apple-II	a, b
5	K21	HPMU	
6	K16	HPMU	
7	I06-B	Apple-II	
8	I08	Apple-II	
9	I10	Apple-II	
10	K07	Apple-II	
11	K18	3PW	c
12	K14 SWIFT	MPW	b,c

Notes: (a) Built in-house, (b) Flagship beamline, (c) no motion control

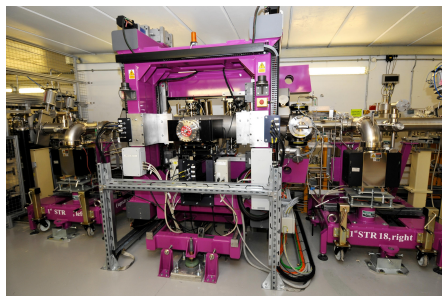


Figure 1: Photograph of an insertion device using the original structure.

PHASE II IDS

Table 3 lists the IDs installed in phase II. The mechanical structure of these IDs changed part way though to the *black* structure, because there were extra constraints in size and stiffness that the original structures could not meet [3]. The control system for black structure IDs separate motion control from the protection system by including potentiometers (Variohm VLP/VXP series linear position sensor) that mirror the absolute encoders robustly in cases when the absolute encoders require a reboot after beam dumps [6].

The systems also started using the OMS MaxV motor controller. The more recent devices make use of MaxV controllers capable of reading the absolute encoders directly. This capability eliminates the need of a mechanism to load encoders and simplifies the PLC and EPICS logic to enable motion.

The motion control systems for Phase II insertion devices differ in the following hardware:

- MaxV motor controller (with the exception of I06-B and I22)
- Secondary encoder for all black structure IDs

Table 3: Phase-II IDs in Operation

Beamline	ID type	Controller	Notes
I06-B	Apple-II	OMS58	
I10-B	Apple-II	MaxV	b
I10-A	Apple-II	MaxV	b
I07	CPMU	MaxV	a
I22	IVU	OMS58	
I19	IVU	MaxV	
I09	IVU	MaxV-SSI	b
J09	Apple-II	MaxV-SSI + MaxV	b
I13	IVU	MaxV-SSI	b
J13	IVU	MaxV-SSI	b
I20	Wiggler	MaxV	b

Notes: (a) built by Danfysik, (b) black structure, **bold** indicates IDs staying for Diamond-II

PHASE III IDS

Table 4 lists the IDs installed in phase III. Three of these systems will remain in use for Diamond-II.

Table 4: Phase III IDs in Operation

Beamline	ID type	Controller	Notes
I05	Apple-II	MaxV-SSI + MaxV	a
I08	Apple-II	Delta Tau	a
I14	IVU	MaxV	
I21	Apple-II	Delta Tau	a
I23	IVU	MaxV-SSI	a

Notes: (a) black structure, **bold** indicates ID staying for Diamond-II

These devices were built using the black structure with the exception of I14 that is using as a source a “spare” ID liberated when I13’s specific ID was installed. Figure 2 shows an example Phase-II ID.



Figure 2: Photograph of an insertion device using the black structure.

The systems started using the Delta Tau motor controller (*brick controller*) to replace the MaxV along with the use of Linux for the EPICS IOC running on a 1U server.

ID I02 CONTROLS UPGRADE

ID I02 had its control system upgraded as part of the DDBA project in 2014 [7].

These components replace the VME based EPICS IOC and motor controller.

- 1U rack-mounted server
- Linux for EPICS IOC
- Delta Tau “brick controller”
- Zebra box

The Zebra box [8] was specially modified to allow the motor controller to operate on the SSI encoder signal while simultaneously passing the encoder information to the protection PLC. This arrangement simulates the arrangements of Phase II *black structure* control systems.

The Delta Tau brick controller replaced the VME based OMS58 motor controller while keeping the control of the amplifier drives using a velocity demand analogue signal. The choice was based on the motion controller solution of the late Phase III systems.

The modifications also reduced the space used from two racks down to one. This reduction of space is also valuable for the Diamond-II project because it liberates space in the controls and instrumentation areas. This space is important for the larger number of power supply controllers needed.

A similar work to upgrade VME-based control systems is discussed below.

UPGRADE PROGRAM AND CONTROLS DEVELOPMENT PROJECT

An extensive development program [4] has been in progress at Diamond. Table 5 shows the IDs installed as part of this work. The control systems use the Delta Tau brick controller but have changed to the CK3M when the brick controller was discontinued.

Table 5: IDs installed in the upgrade program (as of Sept. 2025)

Beamline	ID type	Controller	Notes
J02	CPMU-5	CK3M	
I03	CPMU-2	Brick controller	
I04	CPMU-4	CK3M	
J04	HPMU	Brick controller	a
I24	CPMU-3	Brick Controller	
	CPMU-1	Brick Controller	b

Notes: (a) built by Kyma (b) currently being reworked and planned to be installed in I03 end 2025

ID J04 was built by Kyma [9] and it is an outlier in that the control system was not made in-house.

An insertion devices control system research and development project was undertaken from 2019 to 2023 to prepare for the Diamond-II upgrade. The aims were

- build a test rack
- explore a number of control systems to deploy on existing insertion devices.
- evaluate different motion actuators
- evaluate different servo/stepper drives

While not stated in the project proposal we also looked at the deformation of the mechanical structure by placing encoders by the magnet girders of an ID and comparing against the position reported by encoders mounted on the structure columns. Figure 3 shows the lab setup for the tests.

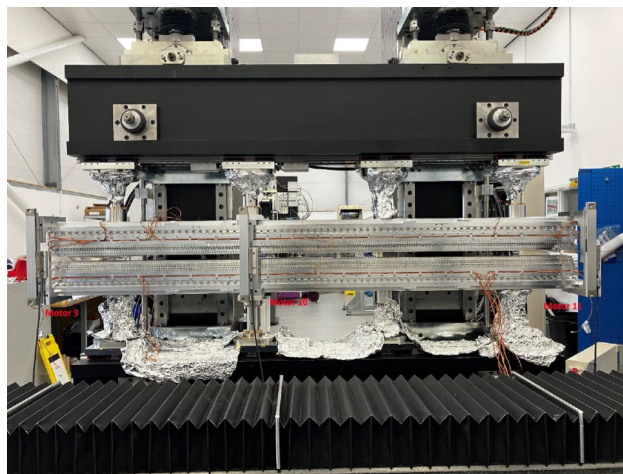


Figure 3: Photograph of the girder deformation test setup.

A test rack was built with test equipment, including a powerbrick controller, a CK3M controller, EtherCAT-capable servo drives from Parker Hannifin, along with a 1U server, terminal server and network switch, largely replicating a typical ID control rack, with the exception of vacuum and temperature control components.

Control was demonstrated using Delta Tau controllers and a Heidenhain 10 nanometre resolution encoder¹ using EnDAT [10]. We also verified operation of this encoder for several months in the storage ring tunnel, as verification of suitability to work in a radiation environment [11].

As control alternatives, the project looked at using EtherCAT to replace the analogue velocity control loop. This was demonstrated successfully using newer versions of the Parker Hannifin Compax3 servo drives.

A significant result was the test of the Powerbrick motor controller to drive a CPMU ID with full magnet load [12], that is with magnets and poles fitted. This was done at room temperature but with a gap of 3.4 mm, chosen to be equivalent to the ID operating cold at 4 mm gap. The tests showed that there is headroom from the maximum current available using the internal amplifiers of the Power Brick. These tests were necessary because Power Brick LV [13]

¹ Model LC415 200 ML ID 689676-04

units at Diamond use 48 VDC². This is lower than the 230 V supported by the Parker Compax 3 amplifiers.

The deformation tests showed that the gap reported using the encoders mounted on the structure differs from the real gap as measured by encoders mounted by the magnet girders [14]. Thus the “gap” figure used may need to be adjusted if one wants to compare this figure against the models. This does not affect beamline operation because the behaviour is repeatable.

NEW INSERTION DEVICES FOR DIAMOND-II

Table 2 lists the IDs to be built for Diamond-II.

The majority of the IDs in the list are planned to be made by industry, however the decision was made that all these will use a Diamond-built control system.

The Apple-Knot ID is notable in the list above, because it is a 5 metre device with a special magnet configuration that makes the mechanical loads higher than previously built IDs. The design uses compound angle magnets causing higher magnetic field for lower photon energy without excessive power on the optics.

The requirements for the Apple-II devices have not been finalised and we are working to verify if the motor controller can deliver the necessary torque for the phase axes and even the vertical axes of the Apple-Knot. Preliminary tests [15] indicate that using the Powerbrick we will not be able to reach the speed that phase axes need and we need to investigate another solution to meet this requirement.

The EMPHU is an electromagnetic/permanent magnet undulator built for fast polarisation switching based on developments made in Soleil [16]. From the motion control point of view the system requires gap control to tune the horizontal field.

UPGRADES FOR VME BASED SYSTEMS

As part of the Diamond-II control system upgrades, we plan to upgrade the VME based systems from using vxWorks to RTEMS.

To reduce the number of motor controllers to support we plan to upgrade the three systems that remain for Diamond-II that would otherwise still use the OMS58 motor controller (IDs I16, I18 and I22).

The chosen hardware for this consists of

- 1U rack-mounted server
- Linux for EPICS IOC
- Powerbrick motor controller
- Omron PLC
- EtherCAT bridge

The equipment mounted on the ID structure will remain installed. The plan is to complete this work before the dark period. The equipment chosen is an updated selection of components that represent a similar upgrade as performed for ID I02 and discussed in the section *ID I02 controls upgrade* above.

OPTICS SYNCHRONISATION

As part of the upgrade of the insertion device for the micro focus spectroscopy beamline (I18) we plan to implement a method to synchronise the ID gap with the beamline monochromator for fast scanning of photon energy [17]. The concept is to have a hardware link carrying the encoder position from the DCM connected to the motor controller of the insertion device. After initial setup the insertion device is changed to a mode where it synchronises according to a compensation table. This has been tested in lab setups without motors and also with a CPMU, in both cases using the CK3M Delta Tau/Omron motor controller.

Only gap synchronisation is needed for the case of the I18 IVU, but the scheme might need to be enhanced to consider synchronisation of the phase motors for the case of the I17 Apple-II insertion device.

CONCLUSION

There are several generations of motion control systems installed in the facility. The motion control systems for insertion devices have gradually changed over the several years operation of the facility. The current design choices benefitted from a program to investigate and test control system options. There has also been work to implement a scheme to deliver optics synchronisation and this will be possible with the upgrades planned. There are still unknowns regarding the suitability of the preferred motor controller, the Power Brick LV, in the Apple-Knot application. The findings from that project will inform the choice for the other five Apple-II devices to be built for Diamond-II.

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