Design, Build & Test of a Double Crystal Monochromator for Beamlines I09 & I23 at the Diamond Light Source

J Kelly¹, T Lee¹, S Alcock¹, H Patel¹

¹ The Diamond Light Source, Harwell Science Campus, Didcot, UK, OX11 ODE
E-mail:  jon.kelly@diamond.ac.uk

Abstract. A high stability Double Crystal Monochromator has been developed at The Diamond Light Source for beamlines I09 and I23. The design specification was a cryogenic, fixed exit, energy scanning monochromator, operating over an energy range of 2.1 – 25 keV using a Si(111) crystal set. The novel design concepts are the direct drive, air bearing Bragg axis, low strain crystal mounts and the cooling scheme. The instrument exhibited superb stability and repeatability on the B16 Test Beamline. A 20 keV Si(555), 1.4 µrad rocking curve was demonstrated. The DCM showed good stability without any evidence of vibration or Bragg angle nonlinearity.

1. Introduction
The Diamond Light Source (DLS) is a 3rd generation, low-emittance synchrotron radiation source. The challenge of preserving the x-ray beam quality with optical elements is demanding. While the Double Crystal Monochromator (DCM) is not a focusing element, it can nonetheless perturb both the shape and position, particularly in the vertical direction, of the x-ray beam at the sample. Typical problems encountered during the operation of DCMs are vibration caused by turbulent coolant flow, heat load and mount induced crystal distortion, non-repeatable crystal motions and slow Bragg axis rotation speeds. These issues were all considered during the design, build and test phases of the project.

2. Specification
The specification was chosen to make the DCM suitable for most beamlines i.e. a general purpose instrument but I09 and I23 are receiving the first 2 instruments; Energy Range: 2.1 – 25 keV, Nominal Power 54 W, Max Power 336 W, Fixed Offset: 16 – 18 mm, Cryogenically Cooled Si(111) Crystal Set, Coarse & Fine 2nd Crystal Pitch & Roll Motion, Suitable for dynamic data capture e.g. Quick EXAFS for high speed spectroscopy.

3. DCM Design
The instrument is mounted upon a natural, black granite block to provide a thermally and mechanically stable support. The Bragg axis is a high stiffness, direct drive, air bearing to provide smooth, fast, accurate positioning, ideal for dynamic data capture. A 66 pole ETEL [7] torque motor in combination with an ultra-high resolution, 5 nrad, Renishaw [6] TONIC™ encoder, enable a high accuracy and static stability. The dual readhead encoder system provides a ± 1.6 µrad installed accuracy over 360°. The air bearing is external to the vacuum chamber. The rotation passes through the vacuum envelope via a ferrofluidic seal. The vessel and Bragg axle assembly are mounted on air
pads to enable repeatable alignment and manual horizontal translation. The internal support structure and 2nd crystal radiation shield (See Figure 1) are thermally stabilized by a water circuit controlled to ± 0.02 K. The design used as starting points, the DLS FOCUS crystal cage installed on I18 [1] and the I20 monochromator axle [2]. The 2nd crystal translation is a custom stepper driven crossed roller slide. The pitch and roll Picomotors™ are driven in closed loop with Renishaw angular encoders, mounted co-axially with the flexural hinges (See Figure 1). The piezo actuators are mounted to oppose the Picomotors.

3.1. Crystal Cooling

It is generally recognised that side cooling of the first crystal gives an effective thermal solution [3] [4] [5]. The 1st crystal manifolds are clamped against the crystal via through holes to minimize manifold bending. The assembly is designed to operate with a 36 W/mm² flux from the beam, with a nominal 1 mm x 1.5 mm beam size. Helical flow enhancers were braised into the manifolds to increase the heat transfer coefficient.

To minimize vibration the 2nd crystal is cooled from one of the 1st crystal manifolds via Cu foil stacks. The 3 stacks of 50 µm foils offer a higher flexibility and conductivity than the standard crimped braid assemblies, due to the superior interface properties. The crimp joint of a braid assembly has a higher contact resistance than a clamped stack of annealed foils even when it is potted with soft solder. The measurement of flexible thermal link conductance has been performed to aid numerous DLS design projects. The study will be submitted for publication in the future.

4. DCM Performance Investigation

4.1. Laser Autocollimator Motion Tests

A full range of individual and complete assembly motion tests were performed in experimental hall build tent. The Y (perpendicular) slide demonstrated repeatable 100 nm step closed loop performance. An undesirable 10 µrad hysteresis in the coarse Pitch was measured. If the scan range was kept constant, the hysteresis was very repeatable. A 4 µrad drift was observed during the Roll measurement. Proprietary flexural hinges were employed in the crystal cage design. The pair of crossed flexures created a stiff but over constrained system. A slight misalignment of the hinges due to machining inaccuracies of the support plates, caused a translation upon direction change. The parasitic linear motion was then interpreted as a rotation by the rotary encoder causing the closed loop Picomotor™ system to compensate. An example small range data set is given below in Figure 2.

A parasitic pitch motion of 150 µrad over a Bragg range of 5° to 65° was measured by a five bounce autocollimator test, with all other motors de-energised. This reduced to 65 µrad when the 2nd Picomotors were commanded to hold position in closed-loop with the encoders.

No detrimental effect was observed when operating the pitch piezo actuator during the B16 beam tests described later. This is probably due to the piezo running in closed loop with its own strain gauge rather than the axis optical encoder. The coarse motion pico motors must be run in closed-loop as the step size depends upon load.

Laser Vibrometer measurements were made through 2 viewports with a range of cryocooler and chiller speeds. The fundamental frequency at the crystal cage was due to a Bragg bearing support Yaw mode at 21 Hz. It was possible to tune the cryocooler on or off the resonance.
Figure 2: Laser autocollimator 2\textsuperscript{nd} crystal motion test data for 2 cycles: a) Coarse pitch ± 180 µrad b) Coarse roll ± 180 µrad, no hysteresis observed over this roll scan range.

4.2. B16 Test Beamline Investigation
The I09 DCM was installed at the end of the B16 (DLS) experimental hutch in order to investigate the effects of the cryo-cooling and clamping on the 1\textsuperscript{st} and 2\textsuperscript{nd} crystal planes. The repeatability and stability of the mechanics under a range of operating conditions was also tested. The experimental setup is illustrated below in Figure 3.

The B16 DCM Si(111) crystals were tuned to 20 keV for all the results presented. The channel cut and the I09 DCM were tuned to the Si(333) reflection; which has a FWHM of 3 µrad. A script was run overnight to alternately optimize the main Bragg angle and the 2\textsuperscript{nd} crystal pitch every 15 minutes.

Figure 3: DCM Test setup on the B16 test beamline. The Ion chamber gave the I\textsubscript{0}. The Scintillation detector was only 1 m from the DCM.

Figure 4: Channel Cut and I09 DCM set to 20 keV, Si(333), 3 µrad rocking over an 7 hour period: a) Rocking DCM Bragg axis with 2\textsuperscript{nd} crystal stage optimized. b) Rocking 2\textsuperscript{nd} crystal pitch piezo with I09 Bragg axis optimized.
The sub-set of results presented in Figure 4a, show a drift between the channel cut mounted on the diffractometer and the I09 DCM of 1 µrad in 7 hours. This illustrates the fantastic stability of the whole beamline and the repeatability of the I09 DCM. The 2nd plot, Figure 4b, shows the 1st to 2nd crystal pitch repeatability. The pitch maxima drift by 0.5 µrad in 7 hours.

![Figure 5: 109 DCM rocking curve when tuned to a 20 keV, Si(555), 1.5 µrad reflection: a) Rocking DCM Bragg axis in 0.1 µrad steps over 3 scans  b) Rocking 2nd crystal pitch piezo with Bragg axis optimized.](image)

The direct drive air bearing stability resolution and repeatability were demonstrated by three repeated 0.1 µrad step size rocking curve scans. All the presented data were taken with the cryocooler and water circuit running.

5. Conclusion
A cryogenically cooled, scanning DCM was built and tested at DLS for beamlines I09 and I23. The instrument was characterized on the B16 test beamline and exhibited good long term stability and repeatability. There was no evidence of detrimental vibration on the 20 keV, Si(555), 1.5 µrad reflection. The I09 DCM is undergoing beamline commissioning with increasing heat loads. The thermal stabilisation time and drift when the shutter is opened will be measured. The spot position and hence angular stability will be measured 30 m downstream at the endstation.

References
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