A High Precision, High Stability, Four Bounce Monochromator for Diamond Beamline I20

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Abstract

A scanning 4 Bounce Crystal Monochromator (4BCM) is being designed for use on Diamond's I20 (versatile spectroscopy) beamline. The instrument will have two independent axes, the first carrying two adjustable crystal sets, the second a pair of channel-cut crystal sets. All will be cryo-cooled. Repeatability of positioning of +/-300nradian is required of each axis to achieve coordination of better than 1microradian to maintain transmitted intensity. We present the development of the design of a high precision goniometer and describe a prototype we have constructed. Test results for a prototype goniometer supported on an air bearing and driven by a direct-drive motor are shown alongside specifications for the operational monochromator.

1. Diamond beamline I20

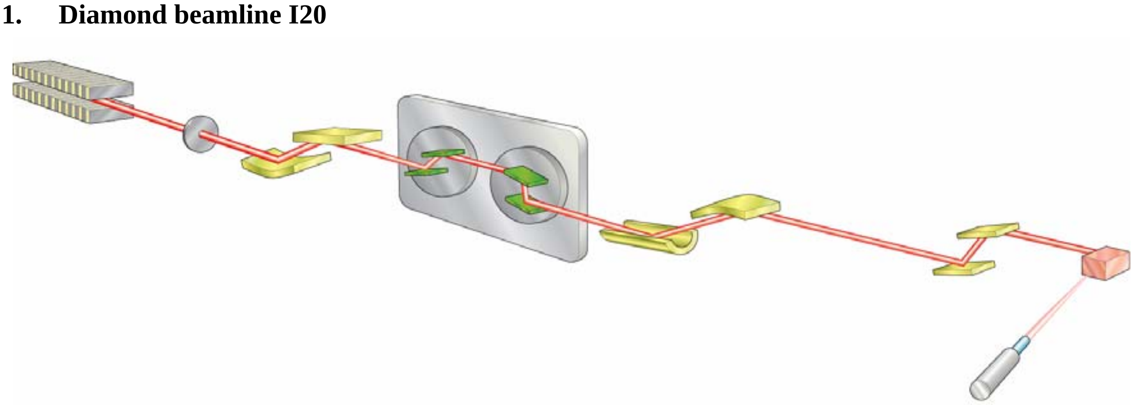


Fig 1. General layout of I20 XAS branch

Table 1. Specifications of I20 XAS branch

Energy range	4-34keV
Band-pass (dE/E)	10^{-4}-10^{-5} with Si(111) and Si(311)
Beam size at sample	~400µm x 300µm FWHM (hxv)
Photon flux	~10^{13} ph/s at 10keV with Si(111)
Energy stability at sample	10^{-4}-10^{-5} with Si(111) and Si(311)
Source	2Tesla Hybrid Wiggler, 2m long
Aperture	0.8mrad(h) x 0.12mrad(v)

I20 is a spectroscopy beamline on Diamond. It has two branches. The XAS line will feature a novel monochromator(4BCM) with a four bounce (+--+) configuration. To cover the energy range it will be equipped with Si(111) and Si(311) crystal sets. The 4BCM is designed to operate under UHV conditions, approx 10^{-8}mbar. It will be fitted with a 500l/s ion pump. A pair of vertically deflecting mirrors (each with Pt and Rh stripes) will collimate and steer the beam to the 4BCM entrance. They will deliver a horizontal, vertically collimated X-ray beam with a maximum heatload of approximately 1000W to the 4BCM. Downstream of the 4BCM a pair of vertically deflecting mirrors will provide a horizontal, vertically and horizontally focussed beam to the experimental hutch. A pair of harmonic rejection mirrors in the EH complete the optical elements.

The specifications for I20 demand a high stability of position and energy selection at the sample.

2. The four bounce geometry

A four bounce monochromator was chosen for this beamline for a number of benefits:
High quality photons; the four bounce geometry gives high energy resolution, even when certain errors are considered.
A fixed exit. The device gives a fixed exit by geometry. No subsidiary motions are required. In its simplest form this monochromator needs only the two Bragg rotation axes.
Technology advancements have made the tight coordination required of the two main axes a realistic goal. In particular, the commercial availability of very large encoders, multipole motors and ferrofluidic seals have made this project technically and commercially feasible.

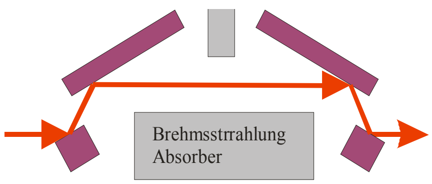


Fig 2. 4 bounce geometry

The geometry of the 4BCM leads to interesting optical performance. One aspect of this is demonstrated by reference to the DuMond diagram of the device's acceptance (fig 3). It can be seen that the resolution of the standard DCM is determined by the width of the entrance slit, which selects a part of the transmission curve of the crystals by limiting the input beam divergence. By comparison, the resolution of the 4BCM is defined by the intersection of the two transmission curves. This obviously limits the divergence of the beam which can be accepted by the monochromator, but does not necessarily limit its aperture. However, it does imply that the performance of the device is dependent on the ability to coordinate the two axes to maintain the throughput. Small errors in alignments generally make very small changes to the resolution or energy of the device, but they do have an impact on the transmission of the device. Fairly small errors can easily reduce throughput by 50%. To investigate the effect of various errors an analytical study has been made[1]. This study has informed the specification of the 4BCM, including tolerances on the installation of the device and its alignment to the X-ray beam.

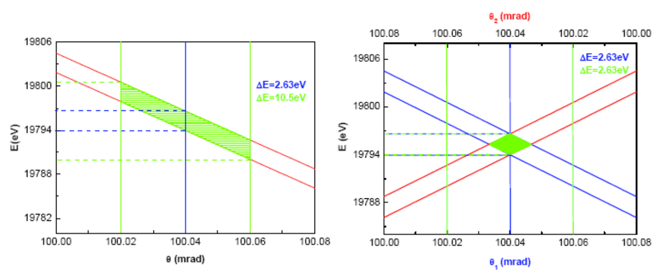


Fig 3. DuMond diagram for DCM. and for 4BCM

3. 4BCM layout and specifications

The layout of the 4BCM is dominated by the two Bragg rotation axes and their vacuum cans. The axes are separated by a distance of 1000mm. To complete the Gas Bremmstrahlung (GB) shielding of the beamline a tungsten stop is required between the two axes. This block is approx 350mm long and will weigh 80kg. It will also be used to stop any white beam incident upon it or scattered from the first crystal pair. The block is split into two parts to allow the addition of a diagnostic in the centre. These will be housed in a central vessel which will also mount the ion pump and vacuum gauging (fig 4).
The instrument will be built onto a massive granite base. It will be able to translate across the beam to allow selection of either crystal set on a short linear air bearing stage. The GB stop must remain static during this translation, so will be mounted through bellows to the base block. At the rear of the instrument liquid nitrogen lines will pass coaxially through the central bore of each of the axes to provide cooling for all crystals.

The crystal cooling will be indirect, to minimise risk, but this will limit the absorbed power to 600W. It will be possible to exchange these for directly cooled crystals in the future to allow the full 1000W to reach the 4BCM.

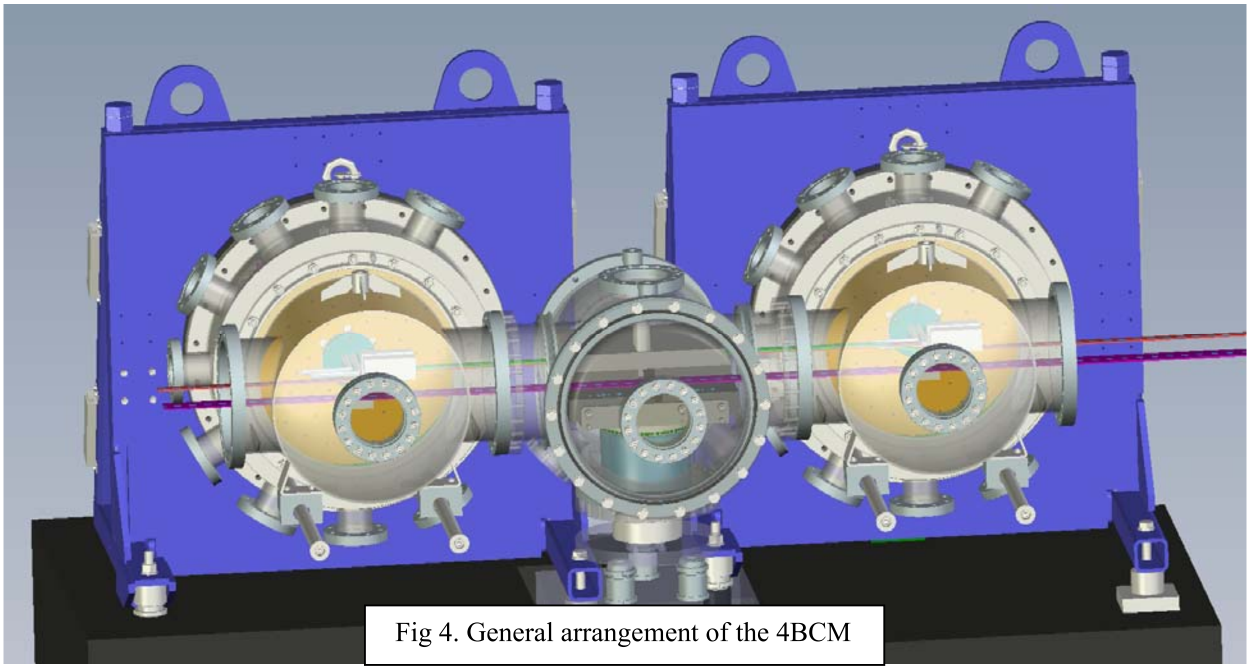


Fig 4. General arrangement of the 4BCM

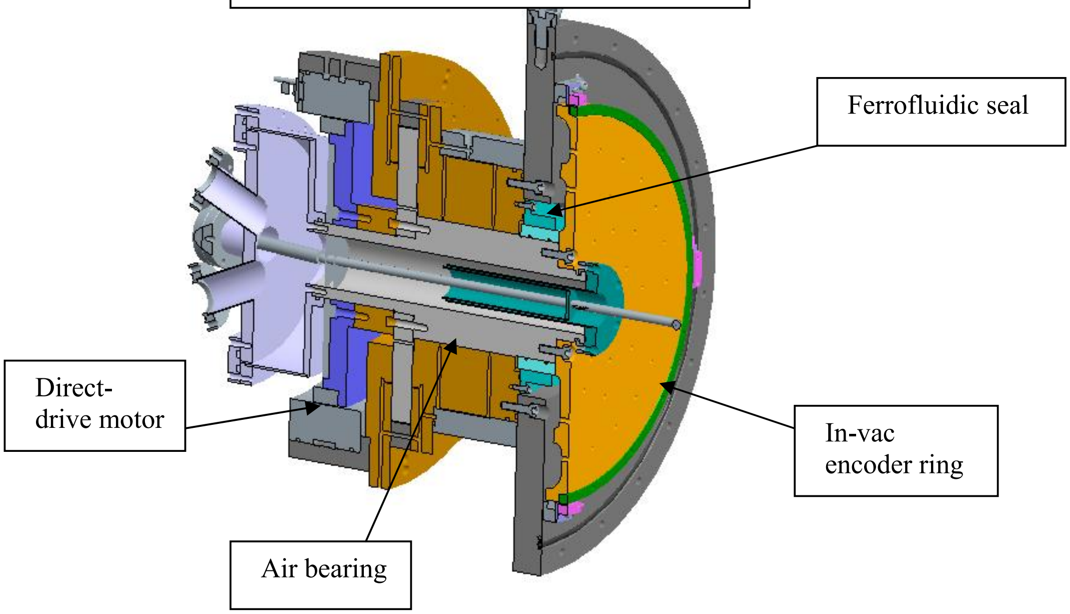
Table 2. 4BCM mechanical specifications

Pitch error between axis 1 & axis 2	1.5μrad	From this is derived the static repeatability of each axis
Static repeatability of each axis	±0.3μrad	
Pitch error between crystal 1 & 2	0.2μrad	
Roll error between crystal 1 & 2	2μrad	
Roll error between first and second crystal pairs	1mrad	Must be aligned with opposite rolls to 100μrad
Pitch adjustment to correct for thermal variation of d-spacing	1.75μrad	

The specs clearly indicate the tight constraints placed on the performance of the two Bragg goniometers, and it is the design of these that we now describe.

4. Goniometer design

Fig 5. Sectioned view of the goniometer



Key components:
The design of the goniometers is based around the combination of five key technologies.

At the heart of the goniometer is an air bearing. This offers excellent performance in terms of runout, rumble, stiction, friction, and repeatability. With no wearing parts, it will also offer consistent long term performance. The axle is actually a combination of two air bearings on a common shaft. A parallel shaft gives high radial stiffness, while a large diameter disk bearing at the tail of the shaft gives high longitudinal stiffness (to resist vacuum forces), and high pitch stiffness. The parallel shaft (125mm dia) is ground from stainless steel to suit a diamond-turned lead-bronze housing to give an air gap of 10micron +/-2micron. A S/S disk is then bolted to the rear of this shaft and lapped to give similar tolerances to a pair of fixed bronze disks. The spacer between the bronze disks is hand lapped to achieve the desired clearances. An air distribution manifold is then created by fitting an aluminium sleeve over the housing. The air bearing is designed and supplied by FFD, Romsey.

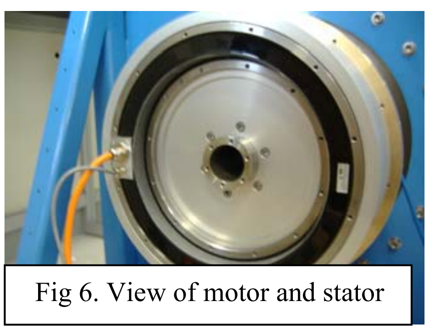


Fig 6. View of motor and stator

A large diameter direct-drive motor is used. The diameter of the motor was chosen not for its torque capability but for its pole count. One lesson learnt from an earlier device was that the pole count of the motor used (12) was felt to be a limiting factor in the performance. In our prototype axis the pole count was increased to 66. The rotor is attached to the shaft by an aluminium disk, bolted at its hub to the tail end of the shaft. The motor stator is attached to an extension of the thrust disk housing. No Hall effect devices are fitted to this motor, which makes for a slightly more difficult task for the control system as it then has no absolute reference for phasing. We have experienced some problems with the control system phasing during the initial testing of our prototype axis. The motor is a standard commercially available unit supplied by Etel.

A ferrofluidic seal is used at the nose of the shaft to provide vacuum isolation. This is supplied as a pre-assembled cartridge and sealed to the shaft and the housing by O-rings. The seal is capable of operation to 10^{-10}mbar and can withstand greater than 1bar differential pressure. The seal was designed for our application by Ferrotec. An added benefit of the ferrofluidic seal is that it introduces a substantial viscous drag to the system. This adds a damping term which makes control at very tight tolerances more straightforward. Because there are no sliding or wiping joints the seal introduces no friction or stiction. The only small area of concern is that the effective viscosity varies somewhat with history. This is because of a characteristic known as clumping, where the ferro particles have a tendency to gather in clumps or strings within the fluid. This increases their stiffness after long periods of inactivity. It is not yet clear whether this will impact on the performance of the device, but if it does it may be necessary to exercise the axes daily or at the start of an experiment.

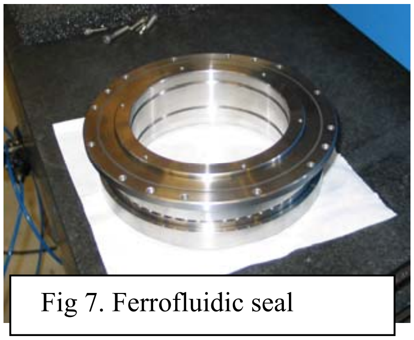


Fig 7. Ferrofluidic seal

Radial clearances within the seal are generous compared with the 10micron radial clearances of the air bearing, so the vacuum will be maintained even if air pressure is lost.

A large diameter in-vacuum encoder is installed to a bronze disk mounted to the nose of the main shaft. The encoder features 20micron line spacing, giving a total of 63800 lines. Our prototype axis is fitted with four in-vacuum readheads mounted at 12, 3, 6, 9 O'clock. Each readhead then has a local interpolator (ex-vac) giving 2000:1 interpolation. Each channel is then capable of a least measurable step of 50nrad. The output from up to four channels may be input into a single controller. This should improve resolution and accuracy, or may be used to compensate for vibration effects. The encoder systems are all standard units supplied by Renishaw.

The motors are controlled by a sophisticated PWM control system. The modules selected (from DeltaTau) are capable of controlling two axes and accepting the inputs from four encoder systems. If we choose to use a maximum of two encoder systems per axis then the whole instrument can be controlled with a single unit. This has certain advantages for improved coordination of the two axes. It may be possible to use additional summing units to add the extra channels and maintain the use of a single amplifier. The drive amplifier will be installed local to the instrument with communication to the control system via fibre optics.
The drive will be hardwire interlocked against loss of air pressure.

5. Prototyping

1.1. Daresbury prototype monochromator

A prototype monochromator (DL4CM) was produced at Daresbury Laboratory with many of the key features used by this design. Key enhancements we have made as a result of the initial testing of the DL4CM have been to increase the diameter of the encoder, increase the diameter and pole count of the motor, and to fit the ferrofluidic vacuum seal. In addition, the crystal cages will be very different as the DL4CM was fitted with water cooled Si(111) channel-cut crystal pairs.

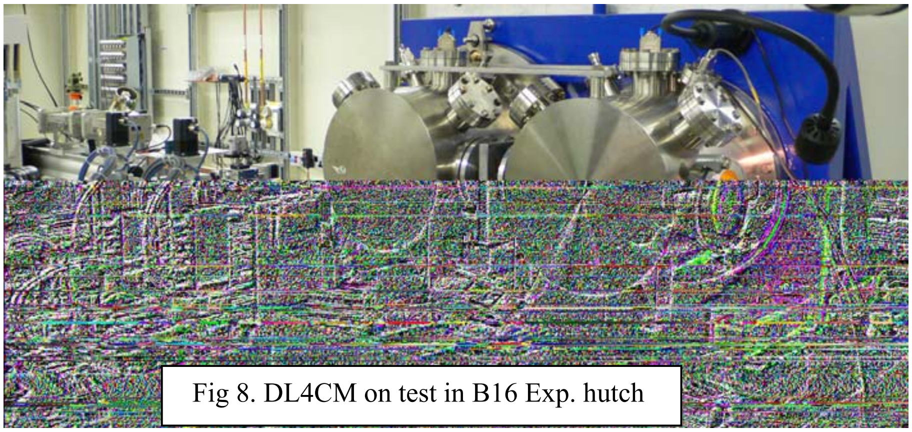


Fig 8. DL4CM on test in B16 Exp. hutch

1.2. DLS prototype goniometer

Initial off-line tests of the DL4CM indicated excellent performance compared to a conventional design, but showed some areas for potential improvement. Notable amongst these were; marginal resolution of the encoders for the resolution required, difficulty in resolving the drive currents with sufficient stability, and vacuum performance. To address these issues a further prototype has been built, of a single axis. In comparison the DL4CM this has; 63800line encoder ring (was 36000), 66pole motor (was 12pole), and a ferrofluidic seal (was a labyrinth seal with differential pumping stage).

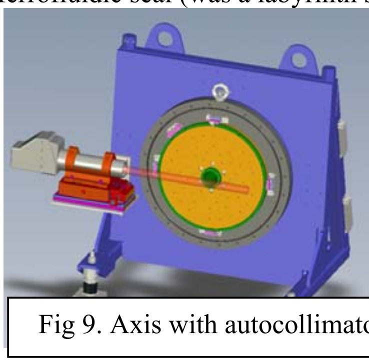


Fig 9. Axis with autocollimator

In addition, the latest control amplifier has been integrated in this prototype.

The axis is commissioned and has been subjected to a number of tests to characterise its performance and compare it with the DL4CM. A large amount of effort was required during commissioning to optimise the control system due to the number of nested feedback parameters. Static performance has reached a good level of performance, but dynamic performance is still being worked on.

6. Testing

Prototype goniometer testing:
A number of aspects of the performance of the goniometer have been explored, including it's static performance (stability and reproducibility of a commnded position), it's vibration performance (continuing), and it's dynamic performance (continuing).
To perform the tests the axis has been equipped with a laser auto-collimator, a high resolution tilt sensor, and an array of seismometers. The control system is also able to report the output of a readhead, either used in the control loop, or a secondary one simply used for monitoring.

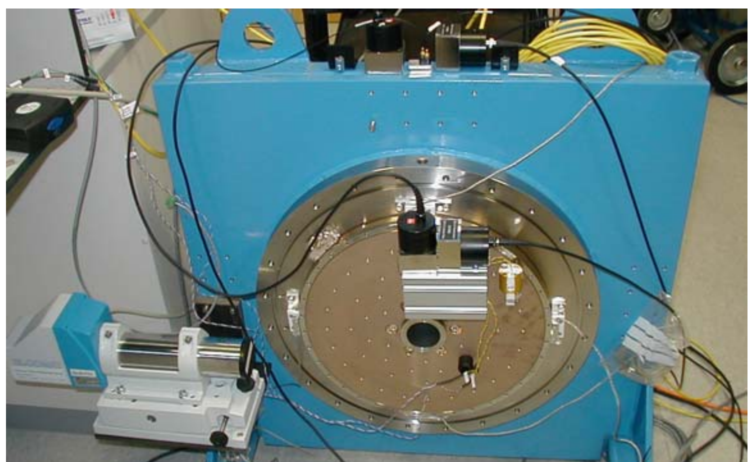


Fig 10. Axis with autocollimator and seismometers fitted

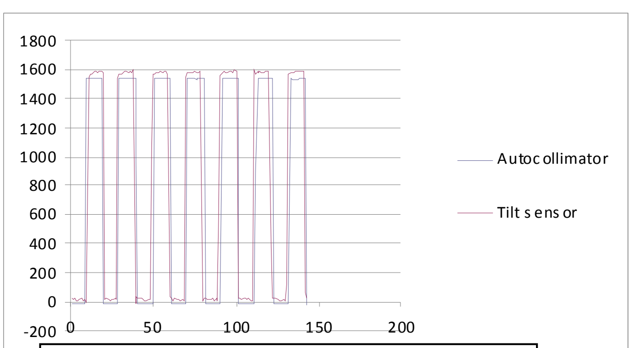


Fig 11. Step & return test results from autocollimator and tilt sensor. Data in µrad, step commanded, 1551.4µrad. Step measured by autocollimator; 1551.6µrad

The resolution of the encoder system installed is higher than that of any of the test equipment, and also has a higher bandwidth, so the autocollimator and tilt sensor have been used to confirm the calibration of the control system and the repeatability of long moves. The output of the control system has then been used to assess the high frequency performance of the axis.
The figure shows a typical test result from a sequence of step and return tests. The error may be explained by the accuracy of the measuring equipment. Long term stability tests also show a performance where any error may be explained by thermal drift of the measuring equipment.

Agreement between readheads is excellent, with very similar results being obtained when the control readhead is used or a secondary one.

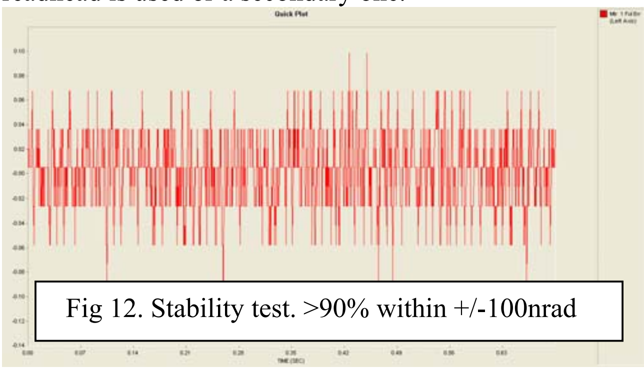


Fig 12. Stability test. >90% within +/-100nrad

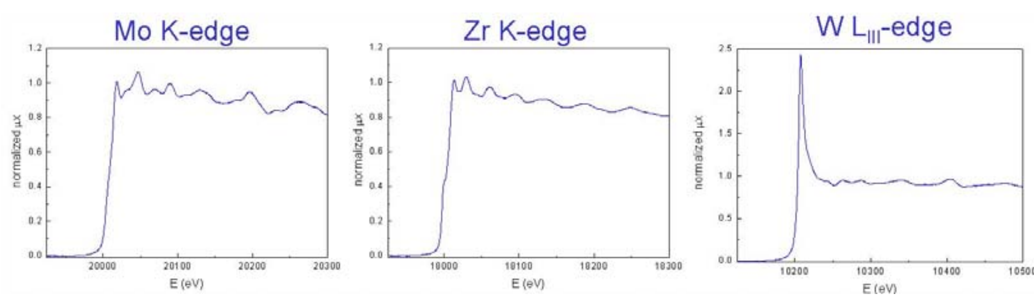
The results of short term stability tests (the capability of the axis to maintain position) have been very good, with +/-100nrad stability. Further tests of long term stability are planned with the addition of a static mirror to enable us to eliminate instrument drift from the measurement. These test will also confirm the ability of the device to repeatably return to a commanded position at two extremes of a very long range motion. Tests to date have shown no measurable error in repeatability.

One interesting result was that, at one point we discovered an unusually large average error reported by the control system. On further analysis it was discovered that the error signal, transformed to the frequency domain, had a strong peak at about 34Hz. This led us to attach seismometers to the disk of the 4BCM and to it's mounting frame. We found that the frame was subjected to an environmental vertical vibration at 34Hz, but that this was not present on the disk. Our assumption is that the oscillation was damped across the air bearing, preventing it's transmission to the disk. Unfortunately, this would then be interpreted by the control system as an error signal and so would be 'corrected', thus translating an external vertical oscillation into a rotary one. We hope that by using the summation of two encoder readheads, symmetrically arranged around the vertical axis, this effect will be eliminated.

Beamline testing of the DL4CM:

The DL4CM was installed on Diamond beamline B16 for X-ray testing. This allowed our first tests with the four bounce configuration under X-ray conditions. The instrument was installed, commissioned, and tested over a week in May '08. A series of tests were performed to conduct EXAFS scans of reference foils for comparative purposes as well as a series of tests aimed to confirm the theory of operation. Analysis of the data is continuing at the time of writing, but initial results are very encouraging.

EXAFS scans covering W L_{III}, Zr K, and Mo K edges were performed, giving good quality data over a range of energies from 10keV to 20keV.



Further analysis of the Mo data shows excellent EXAFS detail and a low noise level of approx 5.10^{-4}, confirming that the motion is free from significant error or jitter.

To conclude, we have proved a number of key technological and engineering design features, as well as proved that the principles of operation are sound. We have work to do to complete the instrument, particularly in the area of crystal design and cooling.

[1] Performance of multi-crystal Bragg X-ray spectrometers under the influence of angular misalignments
J.P. Sutter, G. Duller, S. Hayama, U. Wagner, S. Diaz-Moreno
NIMA 589 (2008) 118–131