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Compensation Of X-ray Mirror Distortion By Cooling Temperature Control

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Abstract. Synchrotron radiation is emitted from a bending magnet source in a wide ray fan which is collected by the first optical element in a beamline. In order to maximize angular acceptance, and hence flux, it is beneficial to increase the length of this mirror and optical design requirements may necessitate that the optical surface be over 1 m in length. Such mirrors also require cooling as they may be subject to high heat loads from the incident radiation. Two beamlines, B07 and B24, at Diamond Light Source, UK, use 1.4 m long toroidal mirrors which utilize a similar side-clamped cooling manifold design. While this scheme has been successful in providing effective cooling of the mirror, it has also been discovered that it introduces deformation of the radius of curvature which is sufficient to alter the focusing characteristics of the mirror. At both beamlines, the horizontal focus of the beam was found to differ by up to several meter from the design position at the exit slit which resulted in poor flux throughput, reduced energy resolution and other side effects. A pencil beam scan method has been used to diagnose this issue and infer the position of the focus and mirror shape. Through the use of a standalone chiller to alter the temperature of the water within the cooling loop, it has been possible to correct the distortion of the radius and restore the focus to its nominal position.

INTRODUCTION

Bending magnet synchrotron radiation sources emit light in a wide ray fan, of which only a portion is collected by an aperture or similar beam-defining mechanism and utilized by the beamline. Since the total flux obtained from a bending magnet source is directly proportional to the angular acceptance of the beamline, it is often desirable to make this as large as possible. However, doing so increases the minimum length required for the first optical element. Since the mirror length is also a function of its distance from the source, placing the mirror as close to the bending magnet as possible reduces the required length somewhat, but it may still be necessary for the optical surface of this mirror to be over 1 m in length. Finally, the grazing angle of incidence also impacts the required length: a larger angle reduces the beam footprint but also reduces overall reflectivity, so a compromise must be made. Further complicating matters, the first optical element of any beamline receives a ‘white’ beam i.e. it comprises the full energy spectrum emitted by the source. Consequently, it is often subjected to a high power load due to the fraction of incident light that is absorbed by the mirror which then causes localized heating of the surface. Therefore, a cooling mechanism is usually required to maintain the mirror at room temperature and this can be a challenging engineering task for such a long optic. Two beamlines at Diamond Light Source, UK utilize toroidal silicon mirrors approximately 1.4 m in length to collect a large angular portion of light from bending magnet sources. A generalized beamline layout schematic is shown in Fig. 1a.

Beamline B07 VERSOX is a versatile beamline that uses two such mirrors to deflect light into separate branches, b and c, which have grazing incidence angles of 1.1/1.3° and collect 2.4/2.0 mrad in the horizontal plane respectively. Both branches utilize a collimated plane grating monochromator monochromator (cPGM)[1] design so the first mirror acts to collimate the X-ray beam in the vertical direction. Beamline B24 serves as the light source for a cryogenically-cooled transmission X-ray microscope (cryo-TXM). Here, the toroidal mirror focuses the beam provide a 1:1 focus at the exit slit. In this case, the position and size of the toroidal mirror is designed such that exactly 2 mrad of the horizontal radiation fan is accepted into the beamline in order to match the phase-space requirements of a zone plate located within the microscope end station. Importantly, the first mirror(s) on both beamlines image the bending magnet source directly to the exit slit i.e. the horizontal focus at the exit slit position is controlled by these mirrors alone.

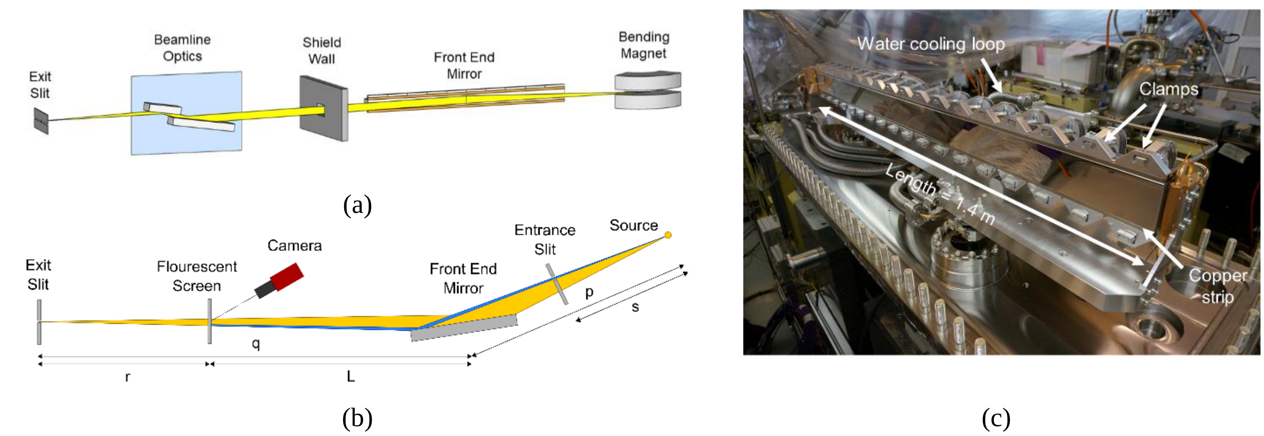


FIGURE 1. (a) Beamlines B24 and B07 utilize similar optical schemes with a long toroidal mirror within the beamline front end. For both beamlines this is the sole horizontally focusing element before the exit slit. (b) The focus position of the mirror is determined using a pencil beam scan where the position of the image on a diagnostic screen is measured as a function of the entrance slit position. (c) Cooling for each of the front end mirrors is provided by a single water-cooling loop which runs along both edges of the optic and is held in place by a series of clamps.

For both beamlines, the distance of the toroidal mirrors from the source requires that they be located within the structure containing the storage ring itself, before the concrete radiation ‘shield’ wall; this region is referred to as the ‘front end’ of the beamline. Space within this area of the beamline is extremely limited, further limiting the maximum length of any mirror module which is installed here. While other mirror configurations, such as a Kirkpatrick-Baez (K-B) mirror pair, were considered for these beamlines, this space restriction makes a single toroidal mirror for both vertical and horizontal focusing an attractive option.

The cooling concept for these mirrors comprises a single loop of water cooling pipe which runs along each side of the mirror close to the optical surface (see Fig.1c). A metal block, which is welded to the pipe itself, sits between the pipe and the mirror surface. This block acts as a thermal interface to transfer heat away from the mirror and into the cooling pipe. The pipe-block assembly is held against the mirror by a series of clamps which apply a pre-set force to ensure a good thermal contact between the silicon and the metal. Some minor differences exist in the B07 implementation compared with the design from B24 (which was built first) resulting from optimizations made to improve the ease of assembly.

DIAGNOSIS OF MIRROR DISTORTION

Fluorescent diagnostic screens located at various positions along each beamline allow the X-ray beam to be observed directly. Since the beam is large at these locations (at least several millimeters), it is relatively straightforward to measure the beam dimensions by utilizing references within the diagnostic modules for scale. These measurements were compared with the expected values from the optical design determined via analytical calculation and through ray tracing using SHADOW[2]. In many positions the beam size was found to differ significantly from expectation, predominantly in the horizontal direction. In addition, the horizontal divergence measured after the exit slit on B24 was found to be less than half of the design value, providing a strong indication that the focus position was incorrect. Systematic re-alignment of the beamline optics was carried out to rule out the possibility of the beam simply being blocked (for example, by a mechanical component within the beamline).

However, it was concluded that there was no blocking of the beam and that the issue for both beamlines was related to the focusing of the front end mirror.

A pencil beam scan method [3–5] was used to determine the position of the horizontal focus. Both beamlines utilize a fixed aperture to define the beam acceptance from the bending magnet source, followed by a variable aperture entrance slit which is used to ‘clean up’ the incoming beam. The horizontal opening of the entrance slit was closed down to ~100 µm so that only a narrow ‘pencil’ beam impinged on both the front end mirror and the downstream diagnostic screen. The slit center was scanned so that the pencil beam moves along the length of the mirror and the corresponding position on the fluorescent screen was recorded.

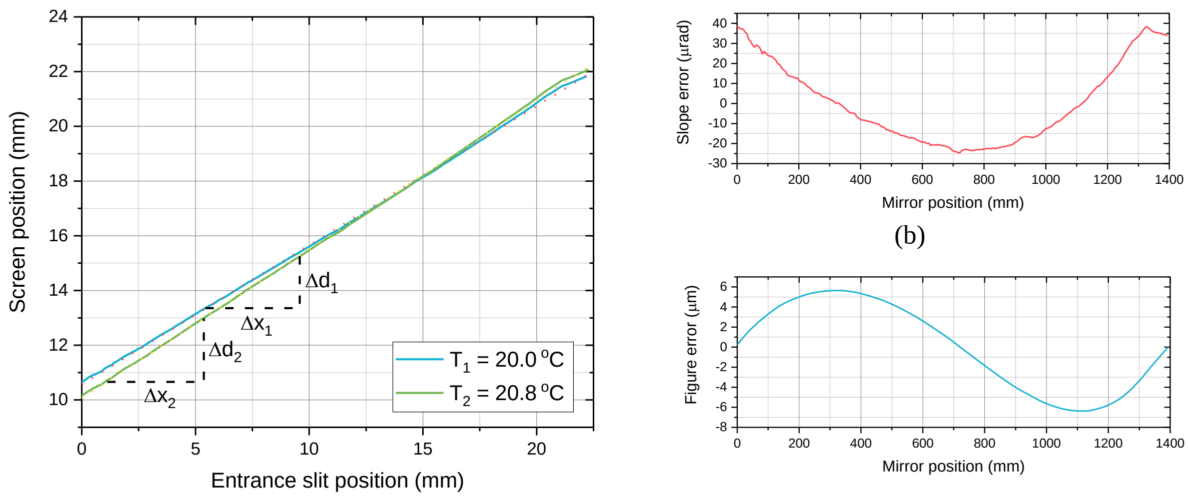
From simple geometrical considerations it can be shown that the position of the mirror focus relative to the screen position r (indicated in Fig. 1b) may be determined from the following expression:

$$r = \frac{L}{\frac{p}{ks} - 1} \tag{1}$$

where L is the distance from the mirror center to the diagnostic screen, p is the distance from the source to the mirror, s is the distance from the source to the entrance slit, and k is the fitted slope determined from a plot of the beam position on the screen d against the entrance slit position x (see Fig. 2a). The focus distance from the mirror q is then simply

$$q = r + L \tag{2}$$

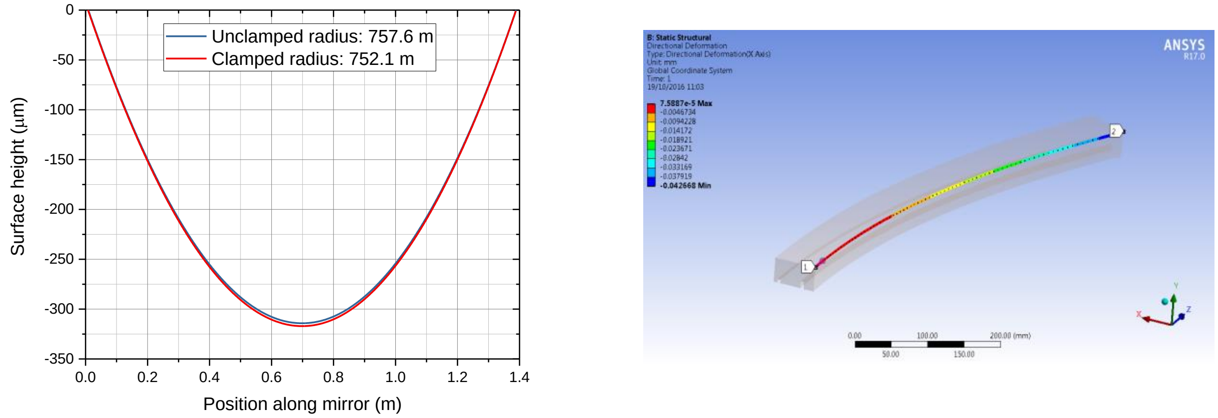
Initial measurements indicated that the focus was approximately 0.7 m downstream of the exit slit on B24, but over 5 m upstream of the exit slit on B07.



(a) (c)

FIGURE 2. Pencil beam scan results from measurements on beamline B24. (a) A slope $k = \Delta d/\Delta x$ is determined from measurement of the beam position on a diagnostic as a function of the entrance slit position. This value is inserted into Eq. 1 to calculate the position of the mirror focus. Such measurements also allow the (b) slope error and (c) figure error of the mirror to be determined in-situ.

The implication of the observed change in focus position is that the mirror radius differs significantly from the design specification. However, metrology measurements of the B07 mirror carried out before installation (see FIGURE 3a) using the Diamond-NOM[6], a non-contact autocollimator-based slope-measuring profiler, showed that the radius of curvature was 757.6 m, very close to the design value of 755.34 m, and well within the ±0.5% manufacturing tolerance. The mirror surface profile was also measured after it had been clamped in its holder with the cooling manifold and the radius was found to be 752.1 m, still within the required tolerance.



(a) (b)

FIGURE 3. (a) Measurements of the mirror surface profile before and after installation into its holder showed that the radius remained very close to the design value (b) Finite element analysis (FEA) software (ANSYS) was used to model the distortion introduced to the mirror by the baking and cooling cycle.

The especially large error in the focus position observed on B07 is attributed to the heat cycle from baking the system, which causes differential thermal expansion of the copper cooling block and the silicon mirror. As the system cools, the copper does not slide back across the silicon surface and instead ‘sticks’ to the mirror, applying an additional force to distort the surface. Since B07 primarily carries out spectroscopy measurements, it is essential to avoid carbon contamination on the mirror surfaces. Baking the mirror chamber (typically at 120°C) improves the ultimate vacuum pressure achieved and reduces the partial pressures of water and hydrocarbons during operation. In the case of B24 carbon contamination is of lower concern so it was sufficient to fit additional pumping capacity to the module to meet the required vacuum level and eliminate the baking requirement.

This conclusion was verified via finite element analysis (FEA) simulations. A simplified model of the mirror system was used for the analysis comprising only the copper blocks and the silicon mirror. The dimensions of these components matched the real implementation and the copper block was modelled as if it was bonded directly to the mirror. The initial temperature of the complete system was set to 100°C and the simulation was allowed to run until the system equilibrated at room temperature. An example of the mirror model from the FEA software (ANSYS) at the end of the simulation is shown in FIGURE 3b.

It was found that when the residual bending radius of the mirror from the simulation was added to the original mirror curvature the overall tangential radius of the optical surface was reduced. The focus distance of the mirror determined from the pencil beam scan measurements was also used to infer the radius of curvature and the values are compared in TABLE 1. The mirror radius obtained from the pencil beam scan and the FEA simulation differ by only ~6% demonstrating very good agreement and supporting the above explanation.

TABLE 1. Comparison of the change in B07 tangential mirror radius determined from X-ray measurements using the pencil beam scan method and from FEA analysis.

Case	Radius Of Curvature (m)	Horizontal Focus Distance (m)
Design	755.34	16.2
Pencil Beam Scan	629.6	11.1
FEA	667.44	12.5

TEMPERATURE CONTROL OF MIRROR DISTORTION

The water running in the cooling loop for the mirrors was initially supplied by the facility main supply which is maintained at a constant temperature of 21.0°C. To enable the cooling water temperature to be altered, dedicated water chillers (Lauda-Brinkmann ECO RE 620 S) were installed for each of the mirrors. These units provide adjustment of the water temperature set point T in the range -20 up to 200°C with temperature stability of ±0.02°C. The temperature set point may be set locally and also remotely (for the chillers installed on B07) via the supplied WinTherm software.

A long term stability test was carried out on B24 to determine how stable the focus remained over the course of several days. For the duration of the test, pencil beam scans were carried out approximately once every hour. The chiller temperature set point was initially set to 21°C to match the main facility supply temperature. After 24 hours the temperature set point was reduced to 20°C. Before the test was concluded the temperature set point was returned to 21°C. The results shown in Fig.4 indicate that the majority of the change in focus occurs within the first few hours after the temperature set point is changed. Following an initial large change, the focus gradually settles to an equilibrium value and after approximately 12 hours it has almost completely stabilized. A tendency for the focus to ‘overshoot’ its equilibrium value is also observed during the initial change period. For the majority of the test the entrance shutter remained completely closed so no beam impinged on the mirror, opening only for the pencil beam scans which take approximately 5 minutes each. However, after the temperature set point was returned to 21°C the mirror was fully illuminated between scans, causing a slight increase in the overall mirror temperature. Consequently, the focus distance was found to settle ~0.1 m downstream of the initial position despite the same chiller temperature set point being used.

A similar test carried out on B07 over a shorter duration showed a similar result, albeit with a much faster settling time: the initial large focus change took only ~1 hour and the focus was stable after ~6 hours. The difference is attributed to the different chiller models used (e.g. stability and accuracy of the temperature control) and to differences in the rate of thermal transfer between the two variations of the mechanical design.

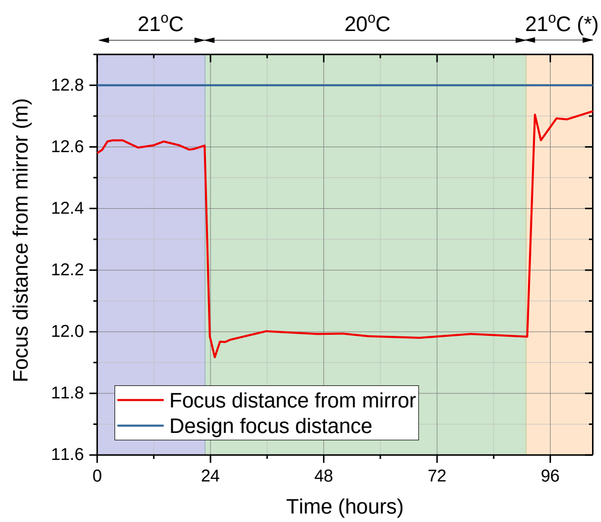


FIGURE 4. Changing the chiller temperature on B24 from 21°C to 20°C was found to change the distance of the focus from the mirror by ~0.6 m. Most of the change occurs within the first few hours after the temperature is altered. Beyond this the focus continues to drift ~0.1 m until an equilibrium state is reached. (*) When the temperature was restored to 21°C the mirror was left exposed to the beam between scans, hence the slight difference in focus distance.

Fine-tuning of the horizontal focus position was achieved by measuring the width of the beam at the exit slit directly and altering the chiller set point temperature until the minimum size was found. Since it was not possible to move the horizontal exit slit blades independently and change the exit slit center position, the pitch angle of a downstream horizontally-deflecting mirror was first reduced by ~0.02° so the beam was offset laterally by ~2 mm. A photodiode behind the exit slit was then used to measure the flux passing through the exit slit while the size of the horizontal exit slit was scanned from its minimum opening (zero) until it was sufficiently large for the entire beam to pass through. Since the beam was horizontally offset due to the change in downstream mirror pitch, the beam was only cut by one of the slit blades so the measurement result was precisely that of a standard knife-edge scan. The result of these measurements carried out at different chiller temperatures are shown in Fig.5.

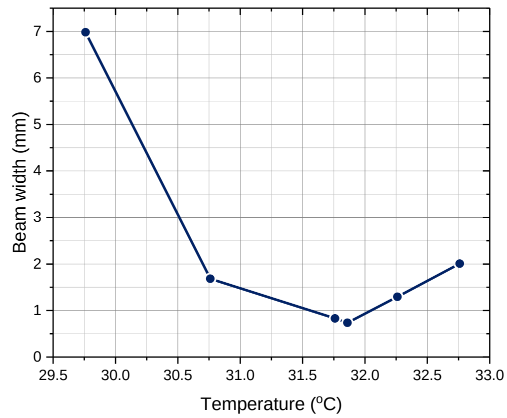


FIGURE 5. Measurement of the horizontal beam width at the exit slit provides an accurate indicator for the temperature which provides the best focus. Final optimization of the chiller set point requires altering the temperature by only 0.1°C.

It was found that the horizontal focus position, and hence the horizontal beam size, is extremely sensitive to the chiller set point temperature. On B07, the final adjustment of the temperature required to find the best focus was only 0.1°C with a minimum FWHM horizontal size achieved of ~700 µm at a chiller set point temperature of 31.9°C. Following this, the downstream mirror pitch could be changed back to its nominal value and since it provides no horizontal focusing the temperature optimization remains valid after the beam is re-centered on the exit slit. On B24, the total temperature change required was much more modest and the best final set point temperature was found to be 20.8°C.

CONCLUSIONS

Use of very long mirrors which are subject to large heat loads presents a significant challenge for the mechanical design of an efficient cooling scheme. The current design meets the cooling requirements for the mirror, but introduces distortion to the mirror optical surface sufficient to alter the focal distance by up to several meters (over 5 m in the B07 case). Clearly this is undesirable, but we have shown that the distortion can be systematically corrected by altering the temperature of the water running through the cooling circuit. Through the use of a chiller with sufficiently accurate and stable temperature control, the focus of the beam can be precisely altered so that the focus is completely restored to the design location. Where a large correction is required the temperature of the cooling water must be changed significantly (by more than 10°C for the B07 mirror), but so far no adverse effects have been observed as a result of long term operation at elevated temperatures. Crucially, this correction method provides a means of restoring the beamline to its design performance without the need to open the mirror module or remove the mirror from the beamline.

REFERENCES

[1] R. Follath, Nucl. Instruments Methods Phys. Res. A **467**–**468**, 418 (2001).
[2] M.S. del Rio, N. Canestrari, F. Jiang, and F. Cerrina, J. Synchrotron Radiat. **18**, 708 (2011).
[3] O. Hignette, A.K. Freund, and E. Chinchio, in *Proc. SPIE 3152* (1997), pp. 3112–3152.
[4] K. Sawhney, H. Wang, J. Sutter, S. Alcock, and S. Berujon, Synchrotron Radiat. News **26**, 17 (2013).
[5] P.P. Naulleau, P. Batson, P. Denham, D. Richardson, and J. Underwood, Opt. Commun. **212**, 225 (2002).
[6] S.G. Alcock, K.J.S. Sawhney, S. Scott, U. Pedersen, R. Walton, F. Siewert, T. Zeschke, F. Senf, T. Noll, and H. Lammert, Nucl. Instruments Methods Phys. Res. A **616**, 224 (2010).