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# Fabrication of Silicon Crystals for a Pin-Post Water-Cooling System at SPring-8

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An internally cooled crystal with pin-post structure was fabricated using sand-blasting methods and Au-diffusive bonding techniques. Test operation at an undulator beamline of SPring-8 showed that the crystal possessed sufficient cooling capability for radiation from the SPring-8 standard in-vacuum undulator. The remaining problem was how to suppress the strain on the surface induced by bonding and water pressure.

**Keywords: X-ray optics; high-heat-load optics; monochromators; internally cooled crystals; pin-post cooling.**

## 1. Introduction

High-heat-load optics are one of the most important issues to be addressed in insertion-device beamlines of third-generation synchrotron radiation sources. For example, the calculated maximum angular power density from a SPring-8 standard undulator (Hara *et al.*, 1998) exceeds 467 kW mrad$^{-2}$ when the stored current is 100 mA. Various efforts to find solutions of high-heat-load problems have been made, including the use of cryogenic cooling of silicon (Bilderback, 1986), inclined geometry combined with liquid-Ga cooling (Lee *et al.*, 1992), and the use of diamond crystals which have high thermal conductivity as well as small thermal expansion coefficients (Freund, 1995).

In SPring-8, solutions using a classical combination of silicon and water have already been sought. One of the most promising solutions was a combination of pin-post cooling (Tonnessen & Arthur, 1992) in rotated–inclined geometry (Uruga *et al.*, 1995). This cooling scheme is known for its very large heat transfer and small pressure drop of the coolant.

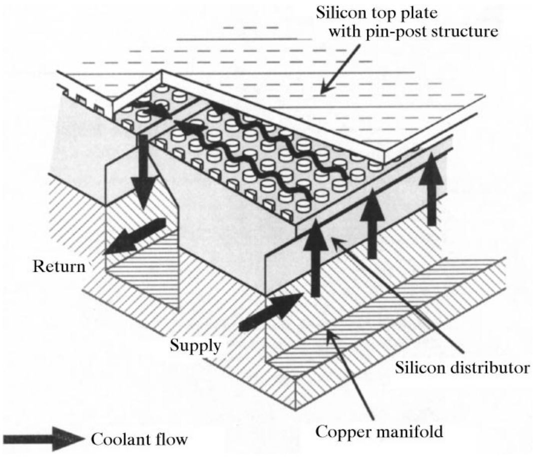


**Figure 1**
A model of the crystal with pin-post cooling structure.

**Table 1**
Geometrical parameters of the pin-post structure for SPring-8 undulator beamlines.

| | |
|---|---|
| Size of crystal (length, width, thickness) (mm) | 150, 65, 15 |
| Area of pin-post structure (length, width) (mm) | 130.7, 50 |
| Pin diameter (mm) | 0.3 |
| Pin height (mm) | 0.2 |
| Pin pitch parallel to flow (mm) | 0.9 |
| Pin pitch perpendicular to flow (mm) | 0.6 |
| Arrangement of pin-posts | In-line |

Here we report recent developments of the fabrication technique of a large-size pin-post crystal for use in a high-heat-load monochromator in rotated–inclined geometry, together with the preliminary results of the first test operation.

## 2. Conceptual design

A model of the pin-post cooling structure is shown in Fig. 1. Interruption of the coolant flow by arrays of pin-posts creates turbulent flow which leads to a large heat-transfer coefficient. The cross flow propagating in the pin-post array is approximated by that in a cylinder array geometry, so we have estimated the performance of the system with a tube-banks model (Zukauskas, 1972). The estimation gave both a large heat transfer coefficient (more than $1 \times 10^5$ W m$^{-2}$ K$^{-1}$) and a small pressure drop (less than 1 kgf cm$^{-2}$) by optimizing the geometrical arrangement of pin-posts and water paths.

The designed geometrical parameters of pin-posts thus determined are shown in Table 1. To obtain a higher efficiency of cooling, the pitch parallel to the water flow was made 1.5 times longer than the perpendicular pitch. Since the footprint of the beam in the rotated–inclined geometry is enlarged, the cooled area is made relatively large. The whole area should be cooled uniformly. For this, parallel water-distribution slots were arranged at an interval of 10.8 mm, which divided the cooled area into 12 sections to keep the pressure drop at a small value (Fig. 2).

## 3. Fabrication

One of the plausible methods of fabricating a crystal with pin-post cooling structure is to stick two silicon plates together; one is the top plate with arrays of pin-posts, and the other is the base plate with coolant-distribution slots. The bonding of these plates should be (i) strain free, (ii) strong enough to withstand the water pressure, (iii) vacuum tight, and (iv) radiation resistive. We adopted sand-blasting methods for pin-post fabrication and Au-diffusive bonding techniques for sticking the two plates together.

The crystals to be used in SPring-8 undulator beamlines were fabricated from 75 mm-diameter FZ silicon ingots with ⟨110⟩ grown axes (Fig. 3). A pair of crystal plates were cut from a single ingot, one of which was used for the top plate of the first crystal, and the other for the second crystal of the double-crystal monochromator. The base plate of the first crystal was cut from another ingot. The size of these plates was 65 × 150 × 15 mm. On the back of the top plate, arrays of pin-posts were fabricated using sand-blasting methods, which realized the designed geometrical parameters except that the diameter of the pin-posts gradually changed from the top to the bottom (Figs. 4*a* and 4*b*). Water-distribution slots of the base plate were fabricated using ultrasonic machinery (Fig. 4*c*). The top and base plates were bonded using Au-diffusive bonding techniques. Before the bonding process, all strains induced by cutting and fabrication of cooling channels were removed by chemical etching, and the surfaces of the top and base plates to be bonded were mechano-chemically finished. Diffusive bonding was made by inserting a gold foil between two crystal plates and applying appropriate temperature and pressure. The reflecting surface of the bonded crystal was polished until the thickness from the surface to the bottom of the pin-posts was 0.5 mm.

A preliminary test using a laboratory X-ray source was made at 17.47 keV (Mo $K\alpha$), without flowing the coolant, by measuring double-crystal rocking curves and taking topographs. Broadening of the rocking curve was of the order of 1 arcsec, which was probably caused by the bonding strain. Net-like patterns corresponding to pin arrays were observed in the topograph.

## 4. Test operation

For test operation, a copper manifold with water inlet and outlet was designed and fabricated. The crystal was mechanically clamped to it with an O-ring water seal and mounted on a standard monochromator of SPring-8. Before installing the crystal in the monochromator, the pressure drop of the crystal attached to the manifold was measured off-line by assembling a simple water loop. The measured pressure drop was larger than the calculated one (Fig. 5). This discrepancy stemmed from the fact that the cross section of the cooling channels is narrower than the designed one. This leads to a higher flow velocity which simultaneously gives a larger heat transfer.

Vacuum tests were made in the monochromator tank installed at a standard undulator beamline of SPring-8 (BL47XU). The pin-post crystal attached to the manifold was mounted on the standard monochromator and

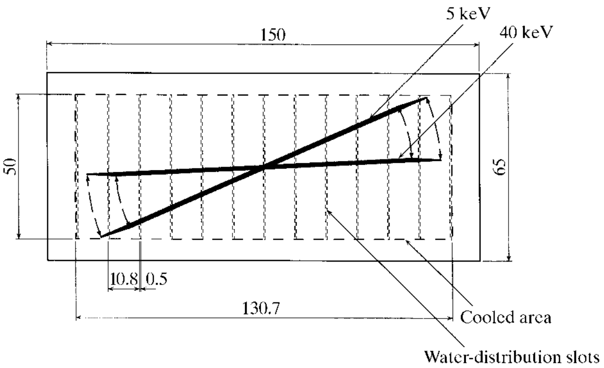


**Figure 2**
Footprints of the beam on the crystal surface in the rotated–inclined geometry. The beam cross section is 2 × 1 mm. The glancing angle of the beam is kept at various Bragg angles from 5 to 40 keV. The cooled area with pin-posts is 130.7 × 50 mm. Parallel water-distribution slots were arranged at an interval of 10.8 mm, which divided the cooled area into 12 sections to keep the pressure drop at a small value. Units of length: mm.

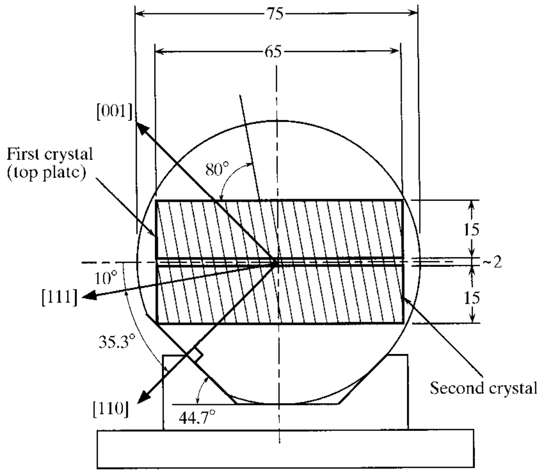
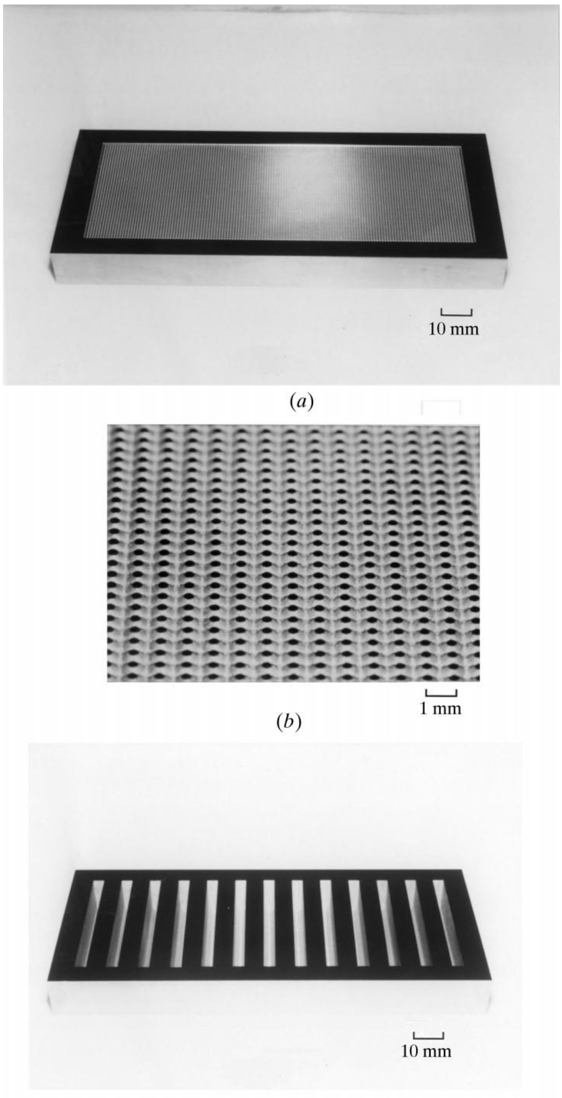


**Figure 3**
Fabrication of the 80° inclined crystals to be used in SPring-8 undulator beamlines. A pair of crystal plates is cut from a 75 mm-diameter FZ silicon ingot with ⟨110⟩ grown axis. The size of these plates is 65 × 150 × 15 mm. Units of length: mm.

connected to the flexible coolant tubes as shown in Fig. 6. The water temperature was set at 293 K and the flow was adjusted to 12 l min$^{-1}$. No change in the vacuum level on flowing the water into the crystal was observed so we concluded that the present bonding as well as the mechanical clamp were vacuum-tight.

A cooling test was made at a beam current of 20 mA and a minimum undulator gap of 8 mm. The angular power density was estimated to be 93 kW mrad$^{-2}$, which corresponded to one-fifth of the designed maximum heat load at 100 mA operation. The temperature distribution on the crystal surface was measured with an IR camera. The temperature of the crystal was unchanged with and without the synchrotron radiation beam. The diffracted intensity of the beam from the double-crystal monochromator became stable immediately after turning the beam on. These observations lead to the conclusion that the cooling efficiency of the present crystal is sufficiently good. A simple extrapolation suggests that it would work well even with maximum heat load.

The diffraction image after the double-crystal monochromator contained a strong line-shaped contrast corresponding to water-distribution slots, in addition to the faint net-like patterns due to the bonding strain of the pin arrays. The measured rocking-curve width for an Si 111 double-crystal reflection at 13.8 keV was 8.9 arcsec, while the calculated value of the perfect crystals is 4.4 arcsec. Rocking-curve broadening due to strains from bonding and water pressure is estimated to be 7.7 arcsec, which is much larger than that observed in the preliminary test. These observations suggest that the major contribution comes from the distortion due to water pressure, so that further improvement of the geometrical arrangement of the water distributors is needed.



(*a*)

(*b*)

(*c*)

**Figure 4**
Crystal assemblies with cooling channels. (*a*) Top-plate crystal. On the back, arrays of pin-posts are fabricated using sand-blasting methods. (*b*) Designed geometrical parameters shown in Table 1 are realized except that the diameter of the pin-posts gradually changes from the top to the bottom. (*c*) Base-plate crystal. Parallel water-distribution slots are fabricated using ultrasonic machinery.

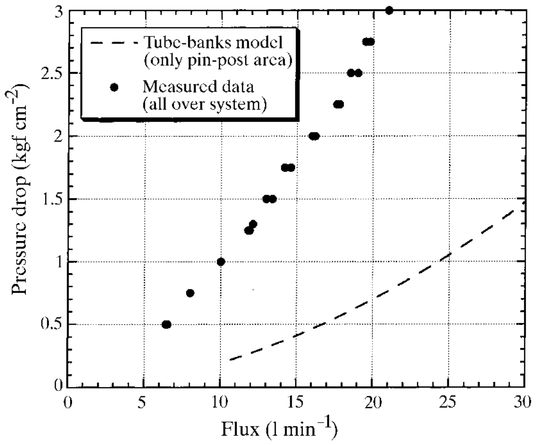


**Figure 5**
Measured and calculated values of the pressure drop for the pin-post crystal. The measured data include the pressure drop all over the cooling channel, but the calculated results only include that in the pin-post area.

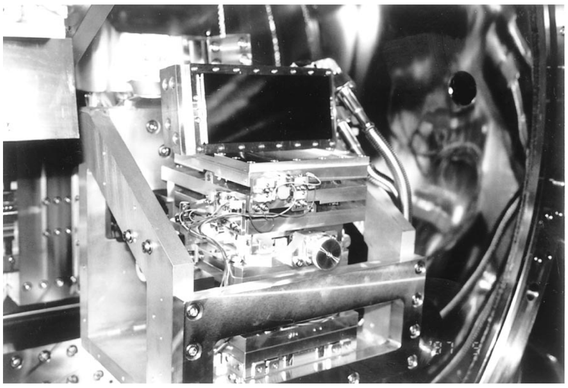


**Figure 6**
Pin-post crystal and manifold mounted on the monochromator at BL47XU.

## 5. Summary

We designed and fabricated a pin-post crystal for SPring-8 undulator beamlines by sand-blasting methods and Au-diffusive bonding techniques. A test in a standard in-vacuum undulator beamline (BM47XU) showed that this crystal has a sufficient cooling capability. Residual strains due to both bonding and water pressure were observed. At the moment, the contribution of the water pressure is much higher than the bonding strain.

Similar crystals have been used at four beamlines of SPring-8 for more than two months of user operation. We have observed no degradation of the performance during this period.

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