PRESENT STATUS OF SPRING-8 CRYOGENICALLY COOLED MONOCHROMATORS

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Abstract

The use of cryogenically cooled monochromators is one of the effective ways of cooling Si crystal that is provided very intense photon beam power of 400 kW/mm^2 from the SPring-8 undulator source. At the SPring-8, the liquid-nitrogen-cooled monochromators are now adopted at ten X-ray undulator beamlines and show satisfactory performance. The design of a liquid-nitrogen-cooled Si crystal and the outline of the circulation system of liquid nitrogen are explained. And the instability in use and the countermeasures are reported.

1. Introduction

Cryogenically cooled monochromator crystals are now in routine operation at the third generation synchrotron radiation facilities, such as ESRF, APS [1-2], and SPring-8 [3]. The cooling of Si crystal can be accomplished by either internal or contact cooling. Both the internal cooling crystals and the contact cooling crystals were developed for the cryogenic monochromator. In internal cooling, liquid nitrogen flows coolant channels configured in the crystal; while in contact cooling, the heat deposited in the crystal is removed by cooling blocks in contact with it. Internal cooling is generally more efficient because liquid nitrogen can flow closer to the heated zone reducing conductive resistance in the crystal. But seal between crystal and manifold is difficult. Although contact cooling is less efficient, the seal of cooling channels are easy and the strain due to mounting is expected to be small.

The radiation power density of more than 400 kW/mrad^2 is still unchanged and the peak heat flux at the monochromator is as high as 100W/mm^2 on the crystal surface. But, the radiation power from the Spring-8 in-vacuum undulator can be reduced from 13kW to 500 W by using front-end-slits. Even if the heat flux is as high as 100 W/mm^2, when total heat load is medium, the heat load on the crystal can be cooled enough by contact cooling. Therefore, the cryogenic crystals of contact cooling are the optimal selection for the SPring-8 cryogenic monochromators.

Two kinds of liquid nitrogen circulation system are employed for the cryogenically cooled monochromators. One is the system to cool the outer-surface of circulating nitrogen pipe with evaporation of liquid nitrogen. The other system uses helium refrigerators to cool circulating nitrogen. Nine refrigerator cooling systems and an evaporation cooling system are now in operation.

Monochromators are expected to preserve the beam stability as well as quality. In the operation of the cryogenic monochromators three kinds of beam instabilities are observed, such as mechanical vibration of the crystals, time dependent peak drift of a rocking-curve and the temporal beam instability. We could suppress the instabilities effectively [4].

2. Liquid nitrogen circulation systems at SPring-8

The first liquid nitrogen circulation system at SPring-8 was installed in R&D beamline 47XU in September 1998, which cools the circulating liquid nitrogen by evaporation of liquid nitrogen. Using this system a prototype of contact cooling crystal assembly had been tested up to a heat load of 693 W with a power density of 76W/mm2. Then a prototype of new circulation system was developed and installed in the high-resolution inelastic scattering beamline 35XU together with a new contact cooling crystal assembly in January 2000. The new circulation system uses helium refrigerators to cool the circulating liquid nitrogen. Each refrigerator has a cooling capacity of 250 W at 77 K. Two or three refrigerators are attached to the system depending on the beamline. The refrigerator cooling systems have been installed in 9 beamlines as of September 2003.

The schematic diagram of the evaporation cooling system is shown in Figure 1(a). The system consists of a liquid nitrogen accumulator, a liquid nitrogen pump, a heat exchanger, and a liquid nitrogen reservoir, and they are assembled in a vacuum chamber. The adjustable parameter is the flow rate of liquid nitrogen. The temperature of the circulating liquid nitrogen is between 79 K and 80 K, which is unadjustable and slightly higher than the saturation temperature of the evaporating liquid nitrogen in the reservoir. The pressure of the circulating nitrogen is kept less than 0.2 MPa and the maximum cooling capacity is more than 700 W.

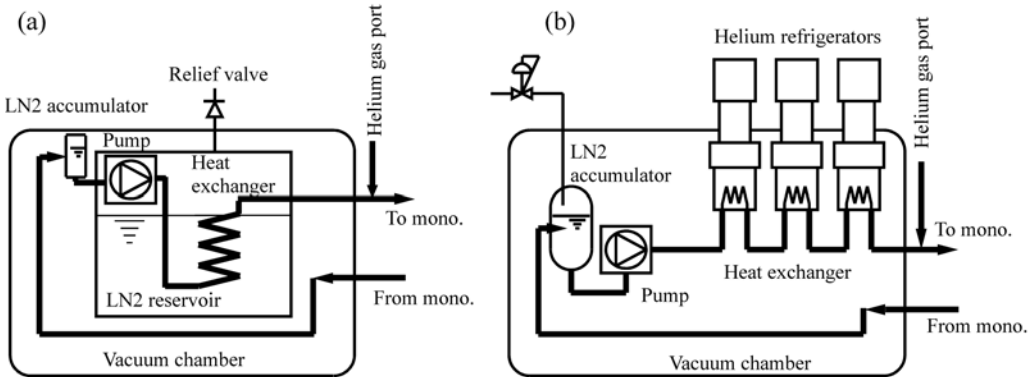

Figure 1*. (a) Schematic diagram of the evaporation cooling system. (b) Schematic diagram of the helium refrigerator cooling system.*

Figure 1(b) shows the schematic diagram of the refrigerator cooling system with three refrigerators. A liquid nitrogen accumulator, a liquid nitrogen pump, and helium refrigerators with heat exchangers are assembled in a vacuum chamber. The adjustable parameters are the temperature of the heat exchanger, the flow rate of liquid nitrogen and the pressure of the accumulator. The temperature of the heat exchanger is set between 68 K and 83 K. The maximum cooling capacity of three refrigerators system is 500W at 77 K.

3. Si crystal assembly

Both the first and second crystals are cooled by contact cooling and have the same design. The crystal assembly is shown in Figure 2.

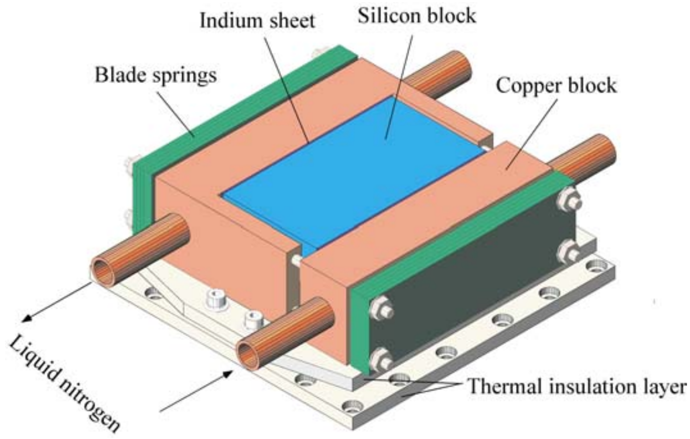

***Figure 2**. The first crystal assembly*

The assembly consists of a Si crystal, two cupper-cooling blocks, two indium sheets, blade springs, screws, nuts and spacer disks. The dimension of the Si crystal is 50 mm wide, 90 mm long, and 35 mm thick. The crystal is cooled by the copper blocks in which the liquid nitrogen pass through. Indium sheets are inserted between the crystal and the blocks to achieve good thermal contact. The blocks are pressed to the crystal by the blade springs. The contact pressure to the first crystal is adjusted to 0.45 MPa by screwing the nuts using a torque driver. The pressure to the second crystal is less than 0.15 MPa.
To estimate the crystal deformation due to the contact pressure a deformation analysis was carried out with a FEM program [5]. Figure 3 shows the FEM deformation analysis result as a contour map at a pressure of 0.45 MPa. The contour map shows the deformation perpendicular to the diffraction surface. Along the longitudinal axis, the deformation distributes less equal 5 nm at the centre region and the calculated slope error is about 0.02 arcsec.

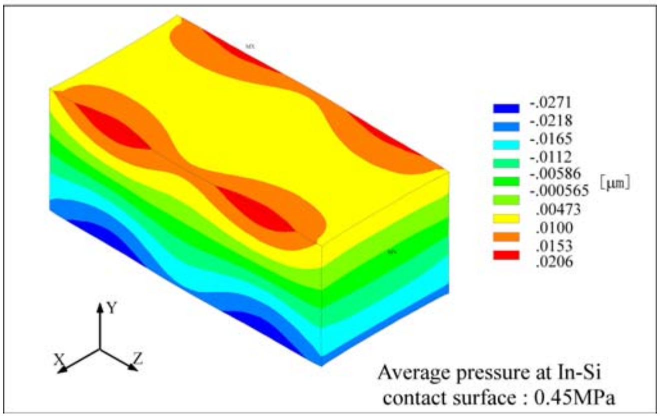

Figure 3. Deformation in Y-direction of a SPring-8 cryogenic crystal with no heat load.

4. Cooling performance

The cooling capability of the SPring-8 refrigerator cooling system is limited by the capacity of the refrigerators and heat loads other than the photon beam, which originated from the liquid nitrogen pump, the transfer tubes, the vacuum chamber, and monochromator stages. Therefore the net cooling capacity was evaluated as 500 W about the three-refrigerator system.

Figure 4 shows the heat load test result at beamline 29XU [4]. It shows the absolute photon flux from the monochromator as a function of heat loads. The heat load was changed by decreasing the stored current from 100 to 1 mA, whereas the aperture of the front-end slits and the gap of the undulator were kept constant. At the ring current of 100 mA, the incident power, P, and the power density, q, at the crystal surface were calculated to be P=478 W and q=27 W/mm^2. The throughput flux increased linearly to the stored current up to 100 mA. It shows that the system including the cryogenic cooler and the crystal assembly has sufficient cooling capacity to remove the heat load of 478 W.

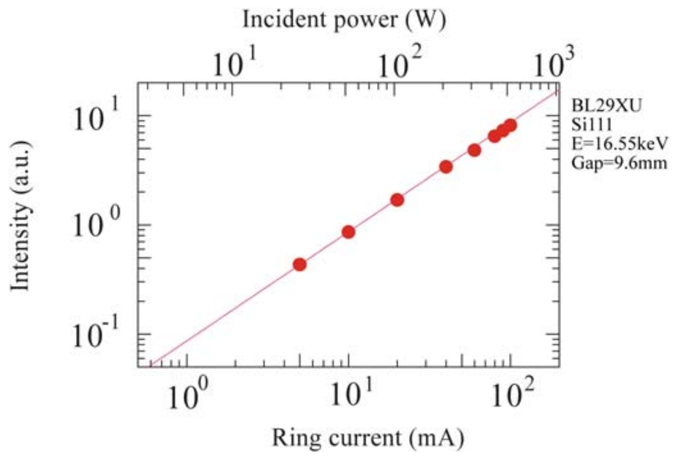

Figure 4*. The ring current dependence on the measured beam intensity.*

5. Beam stability

Three kinds of beam instability were observed at the SPring-8 cryogenic cooling systems. The first is mechanical vibration of the crystals, the second is time dependent peak drift of a rocking curve and the third is temporal beam instability.

The mechanical vibration is crucial problem for the monochromators. It degrades the signal-noise ratio and the effective special coherence of the beam. As long as liquid nitrogen circulates in transfer lines, the flow of the liquid nitrogen itself is the main source of the mechanical vibration. Therefore, it is very difficult to stop the vibration completely. We took some measures to suppress the mechanical vibration, changed the support position of circulating liquid nitrogen tubes, added weight to the tubes, reduced the number of crystal stages, replaced the week stages with the ridged stages and charged helium gas into the circulating liquid nitrogen. At present, the amplitude of the mechanical vibration can be reduced to 0.1 arcsec [6].

The time dependent peak position drift of a rocking curve is caused by the temperature change of crystal stages. Figure 5(a) shows the drift of the rocking curve peak position and Figure 5(b) shows the temperature change of the crystal stages. After the main beam shutter opened, the drift began. It continued for four hours and the peak position shifted more than 30 arcsec. TX2 and TY2 are the temperature of the 2nd crystal stages. They also began to change after the shutter opened. The temperatures increased by 20 K in four hours.

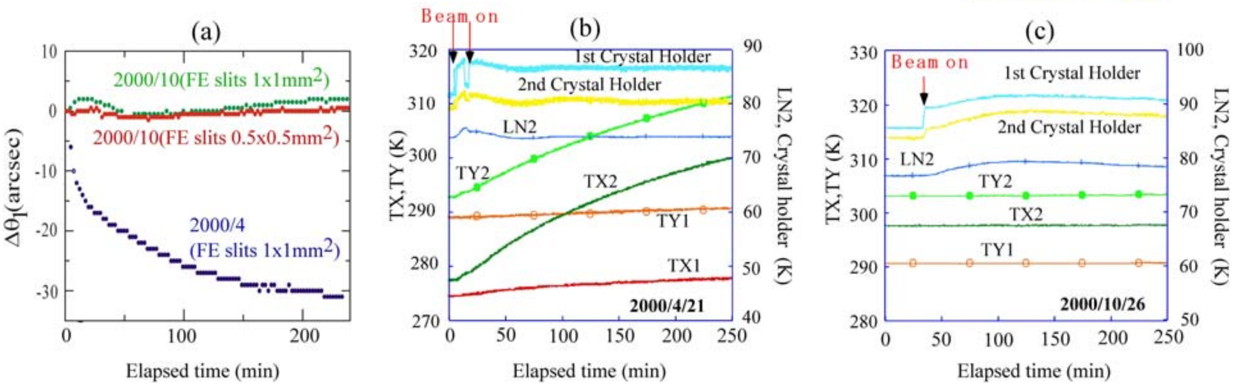

Figure 5. *(a) The time dependent of the peak position of the Si111 first crystal rocking-curve at the photon energy of 18.7 keV measured at constant undulator gap of 10.5mm. Blue solid circles denote at initial state. Red solid circles and green solid circles denote with Compton shield and water cooled copper plate. (b) and (c)The temperature change of the crystal assembly and of the circulating liquid nitrogen. (b) shows the temperature change at initial state and (c) shows the temperature change with Compton shield and water cooled copper plate.*

The temperature changes are caused by the heat due to the Compton scattered X-ray from the first crystal. The reason the temperature change continues for 4 hours or more is because the stages are thermally insulated from the circumference. We placed lead plates on the second stage to shield it. The effect of the shield was restricted. Then we inserted a water-cooled copper plate between the crystal assembly and the top stage of the second crystal. The copper plate was very effective to stabilize the temperature of stages and the output intensity was also stabilized. Although a small drift is observed at higher heat load, green dot data, it is caused by the temperature change of the first crystal stages. A copper plate with heater is also used in other beamlines instead of the water-cooled copper plate and it is effective similarly. Now, the copper plates to stabilize the temperature of the stages are installed in both the first and the second crystal stages.

Figure 6(a) shows the time dependent change of the flow rate and the pressure. The flow rate, Q, and the pressure, P1, fluctuate temporally. This temporal flow fluctuation suddenly happens and it disappears in several seconds after that. Photon beam fluctuates temporally and it is synchronized with the temporal flow fluctuation. This instability tends to occur at lower liquid nitrogen temperature. The effective measure to suppress this instability is to charge helium gas into the transfer line in which liquid nitrogen is circulating. This effect is shown in Fig. 6(b) and it continues for 4 weeks from 2 weeks.

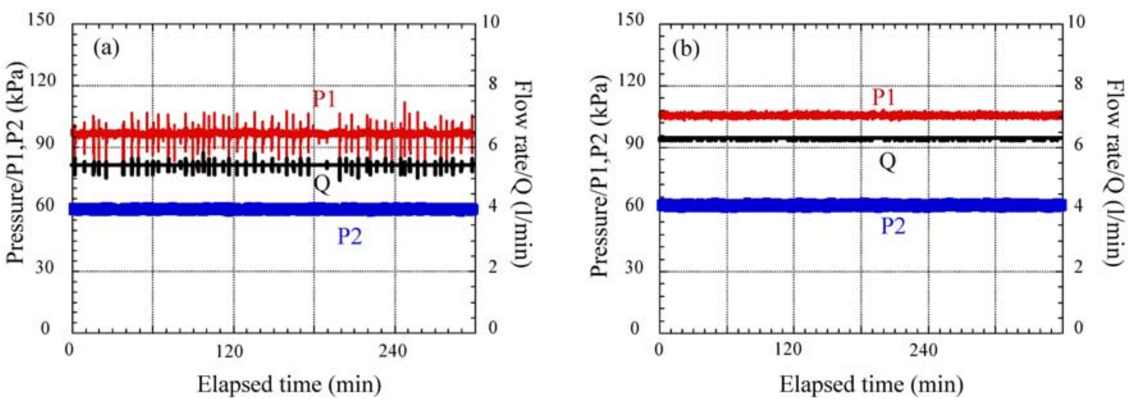

Figure 6*. The flow instability of circulating liquid nitrogen. (a) shows the pressure, P1 and P2, and the flow rate, Q, instability at initial condition, (b) shows the pressure and the flow rate after helium gas charge. P1 and P2 denote the pressure of liquid nitrogen after the heat*

exchangers and the pressure at the inlet of the accumulation tank. Q denotes the flow rate of circulating liquid nitrogen.

Before and after helium gas charge, the inlet pressure of the accumulation tank, P2, is kept constant by a regulator valve. But the pressure, P1, and the liquid nitrogen flow rate, Q, fluctuate. P1 once rises and falls slowly after the gas charge. Q falls slowly and continues for about five hours. It is necessary to readjust a flow rate again so that it may not fall too much after gas charge and it may not become below the alarm setting value of a low flow rate. As for P1 and Q, deviations remain before and after helium gas charge.

6. Summary

Cryogenically cooling systems have been installed in 10 beamlines at SPring-8.
The crystals of contact cooling shows good cooling performance as the monochromator first crystal for the SPring-8 X-rays undulator beamlines, in which the maximum total heat load is 500W with a power density of 100 W/mm2.
The time dependent drift of the rocking curve peak position, which resulted from the heat of the Compton scattered X-rays from the first crystal, was solved with inserting a temperature control copper plate.
The temporal photon beam fluctuation disappeared by charging helium gas into the transfer line.
Although the mechanical vibration still exists, its amplitude can be reduced to 0.1 arcsec.

7. References

[1] D.H. Bilderback, The potential of cryogenic silicon and germanium X-ray monochromators for use with large synchrotron heat load, Nucl. Instrum. & Methods A246, pp.434-436, 1986.
[2] For a review, see D. Bilderback, A. Freund, G. Knapp, and D. Mills, The historical development of cryogenically cooled monochromators for third-generation synchrotron radiation sources, J. Synchrptron Rad. 7, pp 53-60, 2000.
[3] T. Mochizuki, Y. Kohmura, A. Awaji, Y. Suzuki, A. Baron, K. Tamasaku, M. Yabashi, H. Yamazaki, and T. Ishikawa, Cryogenic cooling monochromators for the Spring-8 undulator beamlines, Nucl. Instrum. & Methods A467-468, pp. 647-649, 2001.
[4] K. Tamasaku, M. Yabashi, D. Miwa, T. Mochizuki, and T. Ishikawa, Performance of cryogenically cooled monochromators at SPring-8, Proc. SPIE 4782, pp. 132-142, 2002.
[5] ANSYS, Ansys Inc.
[6] Y. Suzuki, K. Uesugi, N. Takimoto, T. Fukui, K. Aoyama, A. Takeuchi, H. Takano, N. Yagi, T. Mochizuki, S. Goto, K. Takeshita, S. Takahashi, H. Ohashi, Y. Furukawa, T. Ohata, T. Matsushita, Y. Ishizawa, H. Yamazaki, M. Yabashi, T. Tanaka, H. Kitamura, and T. Ishikawa, Construction and Commissioning of A 248 m-long Beamline with X-ray Undulator Light Source, Synchrotron Radiation Instrumentation, AIP Conference Proceedings 705, pp.344-347, 2004.