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A HIGH HEAT LOAD DOUBLE CRYSTAL MONOCHROMATOR AND ITS CRYO COOLING SYSTEM FOR HEPS

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Abstract

A high heat load double crystal monochromator and its cryo cooling system were designed and their prototypes were fabricated for the future HEPS. The mechanical and cooling structure of the DCM are introduced. The FEA results show the DCM is capable of cooling 870 watts of heat load. The cryo cooling system is also introduced. Test results show the pressure stability of the cryo cooling system is less than 2 mbar RMS. Offline heat load test of the DCM were carried out by a ceramic heater attached to the center of the incident surface of the first crystal, and 834 watts heat load were applied by the heater without boiling the liquid nitrogen. Offline absolute vibration measurement of the second crystal assembly was carried out by a laser interferometer under different cryo pump speed, pressure and heat load conditions, to find out the stability performance accordingly. An absolute vibration of 41 nrad RMS was measured, with the pump running at 45 Hz, which has a cooling capability of 400 watts.

INTRODUCTION

HEPS is a new generation light source which employs multi-bend achromat lattices and aims to reach emmitance as low as 60 pm•rad with a circumference of about 1296 m. [1] It will start construction at the end of this year in Beijing. With the new light source there will be very small beam size and high-power density for the monochromator, and cryo cooling of crystals is favourable under those conditions. In the first phase of HEPS there will be 14 beamlines, a batch of cryo cooled monochromators and cryo cooling systems will be needed. Monochromator relates directly with beam intensity and stability issues and affects the overall beamline performance. Beijing Synchrotron Radiation Facility of IHEP is a first-generation light source which contains no cryo cooled optics. It is necessary to develop prototypes of a DCM and a cryo cooling system in order to get a better understanding of the technical challenges during the process and meet the requirements of HEPS beamlines in the future.

The following sections will introduce the design of the DCM and the cryo cooling system, offline heat load test and vibration test, and online test results of the prototypes.

DESIGN OF THE DCM

During the designing phase only, the techniques that had past the proven of principle stage were adopted. By applying those techniques which has never been used in BSRF before, successful running of both the prototypes was the major target.

Table 1 shows the general specifications of the DCM during design phase.

To have a good stability performance wasn't among the original design objectives of the DCM. Later on, after the prototype was built, with the growing concern on the stability performance, the target was set to 100 nrad.

Table 1: DCM Specifications

Parameter	Description
Energy range:	5-20 keV
Crystal type:	Si<111>
Bragg angle range:	-4°–40°
Angular resolution:	0.5 μrad
Fixed offset:	25 mm (upwards)
Absolute stability of exit beam:	100 nrad
Heat load to be handled:	800 Watts
Rocking-curve broadening:	<10%
1st crystal size:	30(W)×60(L)×40(T) mm^3
2nd crystal size:	30(W)×200(L)×30(T) mm^3
1st crystal adjustment:	fixed
2nd crystal adjustment:	Pitch, roll, gap
1st crystal cooling:	Indirect LN_2
2nd crystal cooling:	Indirect by copper foils
Vacuum:	10^{-5} Pa

Cooling of Crystals

To design a high heat load monochromator, a heat load of 870 watts with 2D Gaussian distributions were assumed to irradiate onto the first crystal. Assumed distribution of heat load absorbed on the surface of the first crystal is shown in Fig. 1 and Fig. 2.

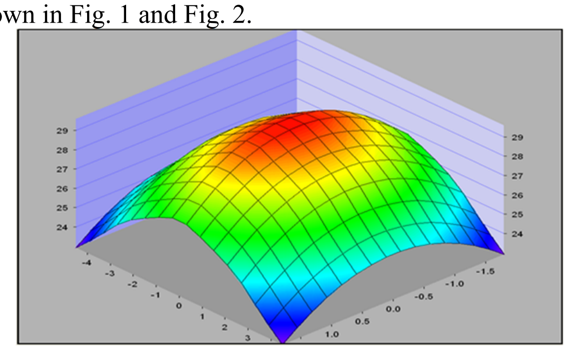

Figure 1: Heat load distribution, total power: 870 watts, power density: 29.6 W/mm^2, divergencies (RMS): 25(H)×10(V) $mrad^2$.

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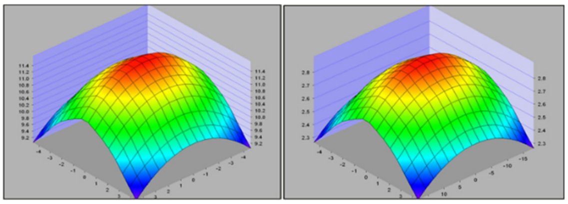


(a) (b)

Figure 2: Power distribution: (a) At 5keV, max power density: 11.7W/mm^2. (b) At 20keV, max power density: 2.9W/mm^2.

Indirect cooling of the first crystal has been proven effective for high heat load monochromators around the world. [2] [3] Designed cooling structure also adopt side indirect cooling by OFHC blocks as shown in Fig. 3. Liquid nitrogen passes through 16 rectangular channels in both cooling blocks. In addition, in order to release the high heat load on the crystal diffraction surface, the height of the cooling copper block was designed to be slightly higher than the upper surface of the first crystal.

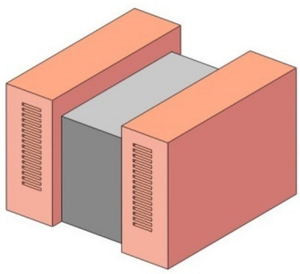
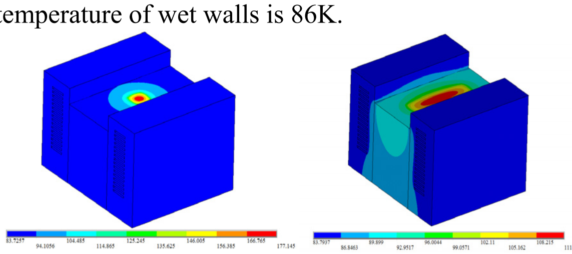


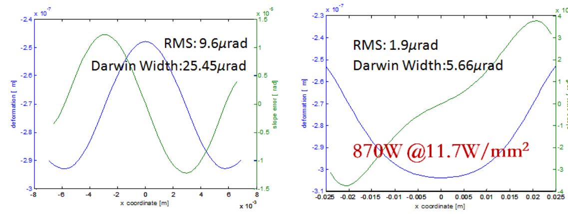
Figure 3: The cooling structure of the first crystal. The first crystal is clamped by 2 OFHC blocks with cooling channels.

The thermal deformation of the first crystal of double crystal monochromator at photon energies of 5keV and 20keV are simulated by FEA. Assuming the thermal contact resistance between the copper blocks and the silicon crystal was 5×10^{-6}m^2•K/W, then the corresponding temperature field can be obtained, as shown in Fig.4. The maximum temperature on the crystal is 177K and 111K, respectively. From the temperature field of the first crystal, the stress field can be further obtained, and then the slope error curve was calculated according to the corresponding strain displacement curve, as shown in Fig. 5. The slope error RMS values of 5.82 μrad and 2.65 μrad for 5 keV and 20 keV can be obtained from the figure, respectively. The deformation results meet the requirement. The maximum temperature of wet walls is 86K.



(a) (b)

Figure 4: The temperature distribution of first crystal at 5 keV (a) and at 20 keV (b).

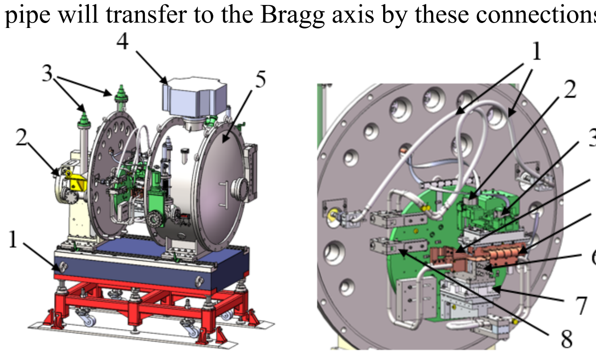


(a) (b)

Figure 5: Displacement (blue curves) and slope error (green curves) distribution of first crystal at 5 keV (a) and at 20 keV (b).

Mechanical Design of the DCM

The designed DCM is shown in Fig. 6 (a). It has a granite table supported by an iron frame, with the frame manual adjustment of pitch, roll, yaw, and height of the main axis is possible. Also 2 slide ways to detach the main axis from the chamber or move the whole Bragg axis assembly transverse to the beam. A worm-wheel Bragg axis from Kohzu was used for good mechanical performance. An ion pump was put on top of the chamber, which now seems hard to maintain and decreases eigenfrequency. The liquid nitrogen in and out flanges are hard fixed to the back plate of the chamber, the vibration of the big hard liquid nitrogen pipe will transfer to the Bragg axis by these connections.



(a) (b)

Figure 6: (a) DCM total assembly, (1) Support chassis, (2) The main axis from Kohzu, (3) Liquid nitrogen in and out flange, (4) Ion pump, (5) Vacuum chamber. (b) The internal view of crystal assemblies, (1) Liquid nitrogen pipes, (2) Pitch adjustment stage, (3) Roll adjustment stage, (4) Compton scattering shield, (5) Copper foils, (6) First crystal manifold, (7) Ceramic heat isolator, (8) Pipe clamp.

The interior of the DCM is illustrated in Fig. 6 (b). Note that the pipes were clamped 3 times to supress resonance. And the temperature difference during low temperature operation was reduced by a ceramic heat isolator. The temperature of isolated part stayed above 270K for a long operation period. A Compton scattering shield was used to protect the second crystal assembly and improve temperature stability of it. The Compton shield worked well after online running. Also heat foils were applied if positive temperature control is required. The first crystal and its manifolds were clamped by bolts with leaf springs to prevent poor thermal contact under low temperature due to shrinkage of the crystal and mechanism.

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THE CRYO COOLING SYSTEM

Table 2 shows the specifications of the designed cryo cooling system. It has more capacity than necessary for future needs, such as the maximum cooling power and the operation pressure.

Table 2: Cryo Cooling System Specifications

Parameter	Specification
Maximum cooling power	2500 watts
Pressure of closed loop	0.2–1 MPa
Pressure of open loop	1 Bar
Pressure stability	$\leqslant \pm 1.5$ kPa
Pump speed	0–100Hz
Maximum flow rate	10 L/min

The system has a closed loop to cool the crystals and a big Dewar in which the heat is taken away by boiling liquid nitrogen via a heat exchanger. The temperature, pressure, are controlled by a heater in a buffer tank. The flow rate is controlled by a variable frequency pump and bypass routes. It can be operated remotely and has full automated process control, which is compatible with EPICs.

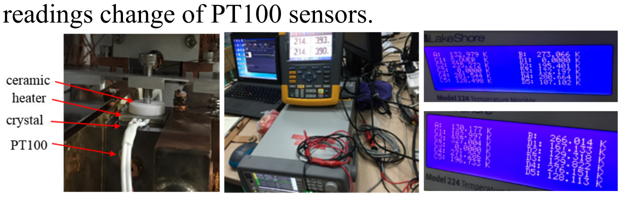
The system will operate at high pressure, to prevent the boiling of liquid nitrogen due to high heat load.

OFFLINE TEST

After the prototype had been fabricated and assembled, the basic functions of them were tested first. After that phase the 2 prototypes were connected together to see how well they perform together. With the tuning and testing we gradually increase the complexity of the tests. First, offline heat load test were carried out, then absolute vibrations of the second crystal assembly were measured by laser interferometers with heat load and other variable conditions.

Offline Heat Load Test

Due to the lack of high heat load beamlines in China, the heat load test was carried out by applying a ceramic heater from Watlow. [4] It has a power capability of 967 watts, dimension of 25 mm × 25 mm. Figure 7 shows how it was applied to the surface of the crystal, the measurement of applied power by a Fluke amperemeter, and temperature readings change of PT100 sensors.



(a) (b) (c)

Figure 7: (a) Ceramic heater applied to the first crystal, (b) Applied voltage and current, 214 V×3.9 A=834 W. (c) Temperature rise of the button PT100 sensor (D5, 107 K–128 K, ΔT=21 K), photo above is before heat load was applied, lower photo is after heat load was applied.

To make sure the heat load was properly absorbed by the crystal, Apiezon N grease was applied between the heater and crystal. [5] Also a ceramic heat isolator was used to keep them tight and isolate heat from going upwards to the support structure.

The measured voltage and current was roughly the given power, how much was absorbed can be calculated by the flow rate and temperature rise of liquid nitrogen flow. By calculation the result was 811 watts. The missing power could have been radiated or passed through the ceramic isolator.

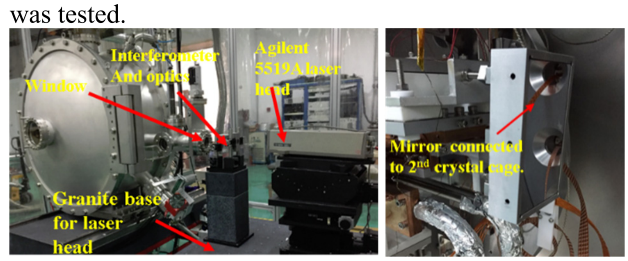
The PT100 sensor was glued to the button surface of the first crystal, the glue is thin, but its thermal conductivity is not very high (about 0.22 W/(m·K) at 77 K). [6] The temperature of the crystal is not measured accurately due to temperature gradient and thermal resistance of the glue.

Offline Vibration Measurement

After the heat load success fully applied and no damage seems to be done, vibration measurements with heat load were also carried out.

The offline vibration test was carried out by a laser interferometer 5519 system from Agilent as shown in Fig. 8. This method was used to test the Petra III monochromators. [7]

Both the absolute and relative vibration affect the beam quality. Unfortunately there is just one port can be used to measure the absolute vibration of the second crystal. Since it requires adjustments of mirror when changing the Bragg angle under test, only when the Bragg axis is at 0 degree was tested.



(a) (b)

Figure 8: (a) Layout of absolute vibration measurement of the second crystal assembly. (b) Mirror mounted onto the second crystal assembly in the vacuum chamber.

The sampling rate of the interferometer was set to 10000 Hz, and the total points could be collected by the software was 1 million, that gave us 100 seconds of collection time.

The vibration tests were carried out under various conditions with different pump speed: (a) Pressure set to 3.5 bar. (b) Pressure set to 4 bar. (c) No heat load, with motor powered on, pressure at 4 bar. (d) 800 watts of heat load, with a 1-minute period triangular wave. (e) 800 watts of heat load applied in a 1-minute period triangular wave fashion. Also, the pure environment back ground was measured without liquid nitrogen flowing or air conditioner running. The air conditioner of the experiment hall increases the vibration level by about 6 nrad, that's why it was shut down to provide a quieter environment.

Figure 9 shows different results under different conditions. The background level is about 29 nrad, given by the

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poor environment of the experiment hall ground with no isolations. However, Sorbothane pads were used under the whole DCM assembly aiming to bring down the vibration [8]. From the figure we can see that the 800 heat load didn't bring up vibration, so the liquid nitrogen was not boiling, the cooling of the crystal was sufficient enough. The best value is 41 nrad and under that pump speed of 45 Hz, which is still very high frequency. By calculation of the liquid nitrogen flow rate and boiling temperature, 400 watts could be taken away before liquid nitrogen boils in the pipe.

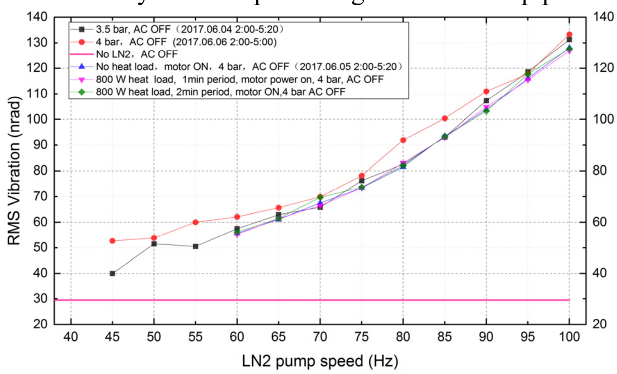

Figure 9: Absolute pitch vibrations under different test conditions. The frequency range is 2 Hz-5000Hz.

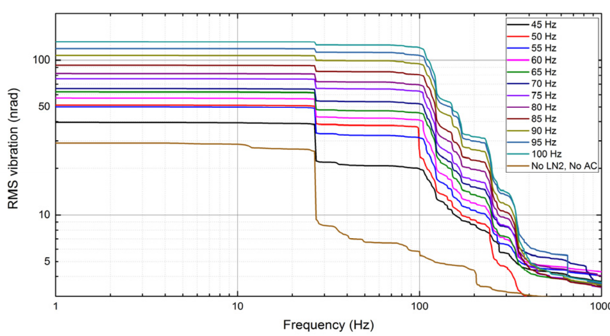

Figure 10: RMS vibrations under different pump speed. The frequency range is 1 Hz to 5000 Hz, but for a clear display the frequency above 1000 Hz is hidden because the values are too small, nearly negligible.

Figure 10 shows the RMS vibrations under different pump speed.

As illustrated in Fig. 10, we can see that the liquid nitrogen mainly contributes mainly to the frequency above 100 Hz. Vibration increases with the increasing pump speed above 100 Hz.

Another thing from the figure it is easy to see that the 25 Hz contributes almost the same at every pump speed, even when there is no liquid nitrogen. It has a contribution of roughly 20 nrad to the total RMS value.

The interferometer optics were mounted by screw rods on magnet base, not hard connected. The magnet base sticks on an iron plate supported by a granite table which stands on 4 levellers. The optics itself has some level of vibrations. As described above, the 25 Hz vibration doesn't increase with the pump speed, so it may be not coming from the DCM itself. It is reasonable to consider 25 Hz as the eigenfrequency of interferometer optics, or just a strong ground motion, and consider the 100 Hz as the first eigenfrequency of DCM.

Pressure Stability of the Cryo Cooling System

The cooling system has been running for more than 100 days and seems to be working rather well. During the running period the pressure stability was recorded under various parameters, such as different pressure, speed. Figure 11 shows the pressure stability at 4 bar, in a long term and in a short term. The pressure stability is in the range of ±6 mbar in PV value, and 2 mbar in RMS.

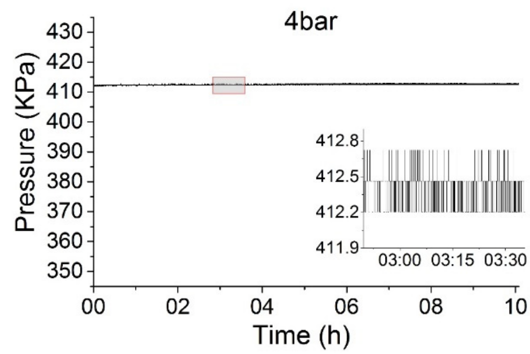

Figure 11: Pressure stability at 4 bar, in a long term (bigger figure) and in a short term (small figure).

ONLINE TEST

Online tests were carried out at beamline 3W1 of BSRF. With a total power of 150W by calculation, only the rocking curve and fixed exit position accuracy can be measured. Test beamline set up is shown in Fig. 12.

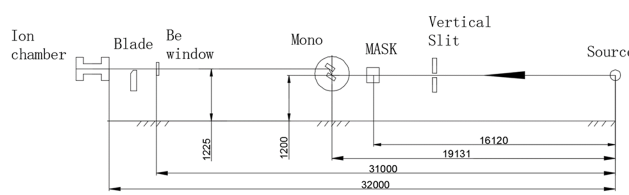

Figure 12: Layout of the online test. The vertical slits defined the acceptance angle by approximately 62 μrad. No horizontal slits but only a mask.

Rocking Curve Measurement

After finding the Cu K edge, the Bragg axis angle could be roughly related to photon energy. Then rocking curve of 5–20 keV were tested by scanning the pitch angle of the second crystal. Table 3 shows the test results. The calculated values were done by XOP. The reason why the measured value are smaller than calculated ones may be caused by the third harmonics from Si<333> diffraction, as shown in Fig. 13. Or it might be caused by miscut, or misalignment of the crystals.

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Table 3: Rocking Curve Test Results

Energy	Calculation	Measured
5 keV	17.78"	15.89"
8.979 keV	8.98"	8.79"
10 keV	7.98"	7.38"
15 keV	5.19"	4.73"
20 keV	3.85"	3.35"

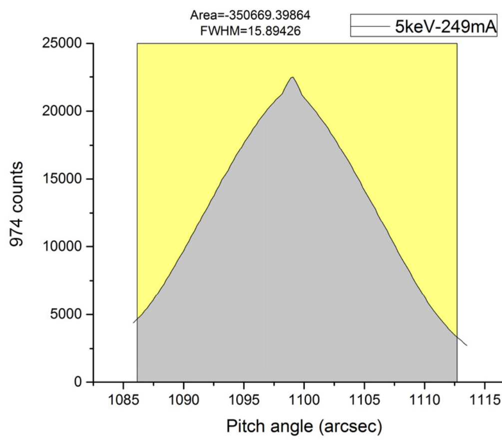

Figure 13: Rocking curve at 5 keV. The small peak on top is signal from 15 keV by Si<333>.

Fixed Exit Position During the Whole Range Scan

The fixed exit position stability during the whole scan was measured by the blade driven by a Kohzu linear stage. The Bragg axis stopped by every 0.5° increment, then the blade scanned the exit beam. During the scan the ion chamber recorded the signal, then derivate the signal, the intensity distribution could be obtained. The beam centre was defined by the FWHM centre of the intensity curve. The result was ±89 µm for a Bragg angle range of 5°–24°.

CONCLUSION

The prototype of designed DCM and cooling system had shown the expected performance and meet our very basic requirements.

As for the stability performance, further stability tests should be carried out to see how it performs under lower pump speed, or on different times. For future HEPS, this will not be the final version of DCM, there are still plenty of room for improvements. The absolute stability is still not good enough for some demanding beamlines which require below 20 nrad stability. And for long term stability of the beam position or intensity, a feedback system and piezo driven flexures should be added.

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REFERENCES

[1] Yi Jiao *et al.*, "Progress in the Design and Related Studies on the High Energy Photon Source", *Physics Procedia*, Volume 84, 2016, ISSN 1875-3892, pp. 40 - 46, doi.org/10.1016/j.phpro.2016.11.008

[2] A. Chumakov *et al.*, "Performance of a silicon monochromator under high heat load", *J. Synchrotron Rad.* 21, 2014, pp. 315 - 324, doi:10.1107/S1600577513033158

[3] A. Chumakov *et al.*, "Performance of a cryogenic silicon monochromator under extreme heat load", *J. Synchrotron Rad.* 11, 2014, pp. 132 - 141, doi: 10.1107/S0909049503026785

[4] WATLOW company website: http://www.watlow.com/en/products/heaters/specialty-heaters/ultramic-ceramic-heaters

[5] APIEZON company website: https://www.apiezon.com/products/vacuum-greases/n-grease

[6] Lake Shore Cryotronics, Inc., https://www.lakeshore.com/products/cryogenic-accessories/varnish/pages/overview.aspx

[7] P. Kristiansen, J. Horbach, R. Doehrmann, J. Heuer *et al.*, "Vibration Measurements of high-heat-load monochromators for DESY PETRA III extension", *J. Synchrotron Rad*, vol. 22, Jul. 2015, pp. 879 - 885, doi.org/10.1107/S1600577515005664

[8] SORBOTHANE company website: https://www.sorbothane.com