Diamond Crystal Monochromator in a SPring-8 Undulator Beamline

Hitoshi YAMAOKA[1), Kiyotaka OHTOMO[1, 2) and Tetsuya ISHIKAWA[1, 3)

1) SPring-8, Kamigori, Ako-gun, Hyogo 678-12, Japan
2) Quantum Equipment Division, Sumitomo Heavy Industrial Ltd., Shinagawa, Tokyo 141, Japan
3) Faculty of Engneering, University of Tokyo, 2-11-6 Yayoi, Bunkyo, Tokyo 113, Japan

Insertion devices in third generation rings give us challenging problems for the beamline components, especially from a thermal view point. If we use a low-Z material as a monochromator the absorbed power of the crystal is much less than that of a Si crystal. Diamond crystal is one of the choices for a monochromator to withstand the high heat load beam owing to its better thermal characteristics compared to that of a silicon crystal. In this report we describe the potential of applicability of a diamond crystal monochromator to a SPring-8 undulator beam through some analyses[1].

We chose a SPring-8 typical undulator with parameters of λ=3.2 cm, Ky=1.66, N=140, L=4.5 m and I=0.1 A for the following calculations, where λ, Ky, N, L and I are period of magnetic field, deflection parameter, number of periods, total length and stored current, respectively. A graphite filter of 100 μm thickness and Be window of 500 μm thickness are set before the diamond crystal monochromator. The total power before the filters is estimated to be 5.56 kW. Power reduction by the filter and the window is less than 10 %. We can reduce the power drastically by one order by using a slit system without missing the on-axis photon flux since the odd harmonics of the photon spectrum are in the center region of the power distribution. A slit size of 1.2x2.3 mm^2 is chosen since it decreases the integral of the total photon flux for first harmonics only about 20 %[2].

The real heat power of the crystal is different from the absorbed power due to the escape x-rays through some atomic processes. Considering the atomic processes of radiative decay, Compton scattering and Rayleigh scattering, the power calculations of each component are performed by using OEHL (Optical Element Heat Load) code. Analytical results at a given incident angle after the graphite filter and Be window are shown in Fig. 1 as a function of the diamond crystal thickness[3, 4]. The radiative decay process is negligibly small. About 22 % of the absorbed photons escape from the crystal. Although the Compton back scattering and transmitting processes are dominant, they are one or two orders of magnitude smaller than the absorbed power. Here we use the pure absorbed power as input power of the crystal for the heat load calculations.

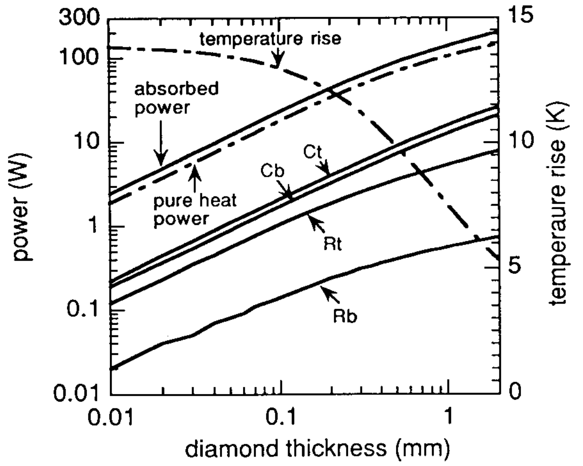

Fig. 1 Power distributions of a diamond crystal as a function of the crystal thickness, where Cb, Ct, Rb, Rt, and HP are the powers of Compton back scattering, Compton transmitting, Rayleigh back scattering, Rayleigh transmitting and pure heat, respectively. Temperature rise calculated by using eq. (4) for the pure heat power at each crystal thickness for the edge-cooled geometry is also indicated.

Thermal analysis of an edge-cooled diamond crystal monochromator is performed to get the order of thermal deformation at first. Assuming a circular diamond crystal and uniform heat deposition throughout the crystal thickness, one can write the differential equation for the heat conduction,

$$k\Delta T + q = 0, \qquad (1)$$

where k, T and q are the conductivity (W/Km), temperature (K) and deposit power (W/m^3), respectively. Cylindrical polar coordinate system with radius r is taken. The equation is solved for r. If we use a slit system of 1.2x2.3 mm^2, the difference of the power is only about 5 % within the slit size although the odd number harmonics have sharp distribution in the center region. For simplicity, we assume uniform heat load of q_0,

$$q(r) = q_0, \quad r \leqq r_0 ; \qquad 0, \quad r \geqq r_0 \qquad (2)$$

We give the boundary conditions that $T=T_w$ at $r= l$, dT/dr=0 at r=0, the function dT/dr is continuous and $T_1(r_0)=T_2(r_0)$ at $r=r_0$, where T_w is the cooling water temperature. The plate is convectively edge-cooled at $r=l$. The solutions of the equation (1) are,

$$\delta T(r) = T(r) - T_w$$
$$= -(q_0 / 2k) r_0^2 \ln(r / l), \qquad r \geqq r_0;$$
$$= -(q_0/4k)\{r^2 - r_0^2 + 2r_0^2 \ln(r_0/ l)\}, \qquad r \leqq r_0. \quad (3)$$

The maximum temperature difference of δT_m is

$$\delta T_m = T(0) - T_w = (q_0/4k)\, r_0^2 \{1 - 2\ln(r_0/l)\}. \qquad (4)$$

This equation indicates that the cooling channel should be as close as possible to the irradiated area δT_m becomes smaller as l approaches to r_0. The displacement along radial direction of δl is

$$\delta l = \int \alpha \delta T(r) dr = (\alpha q_0 r_0^2/6k)\,(3l - 2r_0), \qquad (5)$$

where α (1/K) is the thermal expansion coefficient. The displacement δt is the sum of the thermal expansions along and vertical δt_v to radial δt_r direction of the crystal surface and is approximately given by,

$$\delta t_r + \delta t_v \approx \mu(\delta l/l)t + \alpha \delta T_{r=0}(1/2)t$$
$$= (\alpha Q/\pi k)\{(\mu/6l)(3l - 2r_0) + (1/8)(1 - 2\ln(r/l))\}, \qquad (6)$$

where Q, t, μ and $\delta T_{r=0}$ are total input power which has a relation of $Q = q_0(\pi r_0^2 t)$ (W), crystal thickness (m), Poisson ratio and temperature rise at the crystal center (K), respectively. For simplicity, we take δT_m in eq. (4) as $\delta T_{r=0}$. If the crystal has a radius of curvature R due to the displacement δt at the crystal center, they have the relation $R(1 - \cos\delta\theta) = \delta t$, where θ is angle. Normally $l \ll R$, then the angle distortion, $\delta\theta$ is approximately written as, $\theta \cong l/R = 2\delta t/l$. It should be noted that in this formulation we assume the crystal edge is maintained at the water temperature ignoring the heat transfer coefficient. In Fig. 1 the temperature rise is also indicated as a function of the crystal thickness by using the calculated pure-heat power under the conditions k=1900 W/mK, r_0=1.1 mm and l=1.6 mm. This gives an interesting result that a thicker crystal gives a lower temperature rise and thin crystal is not necessarily best choice in all cases for indirectly edge-cooled crystal with undulator beams.

Three dimensional finite element analysis (by the ANSYS code) under a similar heat load condition as above is performed. We chose a diamond of area of 4x4 mm^2 and thickness of 300 μm at the incidence angle of 60° after a graphite filter and Be window. Considering Bragg reflection, reflection plane of (400) and the Bragg angle of 60°, a monochromatized beam of 8 keV will be obtained. A pure heat load of 46 W calculated by using OEHL code is applied to an area of 1.2x2.3 mm^2 for the incident power of about 620 W and absorbed power of about 59 W. For the analysis the crystal is divided into three parts as function of crystal thickness by calculating the pure absorbed power at each depth. The diamond crystal is held by copper from two edge sides. We assume a heat transfer coefficient of 5000 W/m^2K between the water and the crystal holder and a cooling water temperature of 30°C. In the calculation a perfect diamond crystal is assumed. The crystal holder has a cooling channel 8 mm in diameter. The model used in the analysis of the diamond monochromator is shown in Fig. 2. The maximum temperature raise is about 23 K at the crystal center. From the results the angle distortions are estimated to be about 0.5 arc seconds on the direction perpendicular to the beam and about 0.3 arc seconds on the beam direction. These values are much smaller compared to the theoretical intrinsic rocking curve width which is calculated to be 2.9 arc seconds at an energy of 8 keV for diamond (400). We can compare the analytical treatment in the previous section with these results. If the crystal has a total input power of about 46 W on a diameter of about 0.94 mm, these values lead to the same power density as that in the ANSYS calculation, the angle distortion is estimated to be about 0.6 arc seconds from above equations. This value agrees with the results by the ANSYS calculation. It is concluded that thermal deformation in the power region is less than 1 arc second. Effect of the thermal deformation on the rocking curve width is only about a 6 % increase compared to the intrinsic width.

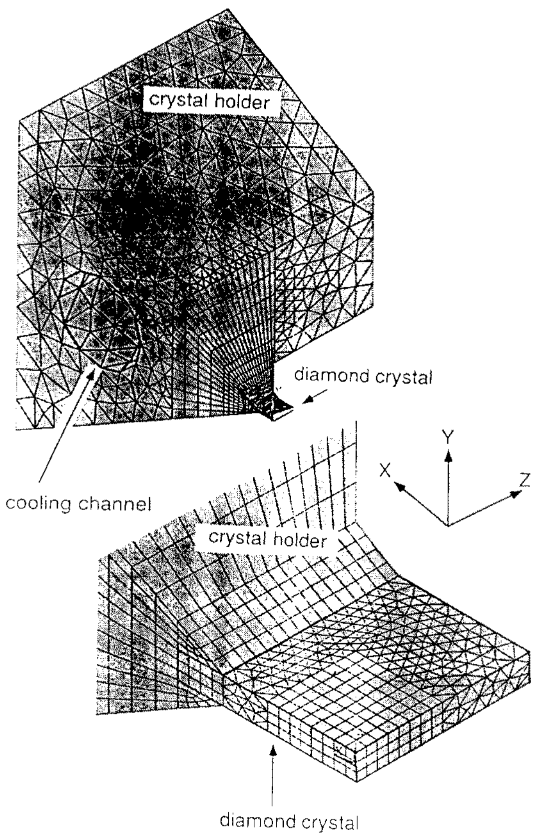

Fig. 2 Analytical model of the diamond monochromator for the finite element analysis by ANSYS (upper figure :quarter model of the crystal and its holder, lower figure :enlarged figure of upper one concerning the part of the diamond crystal). The diamond crystal is held by copper from two edge sides.

References

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