AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

ANL/XFD/CP--82931
Conf-940714--6

Thermal and Deformation Analyses of a Novel Cryogenically Cooled Monochromator for an Advanced Photon Source Beamline

Zhibi Wang, Wenbing Yun, Tuncer M. Kuzay, Gordon Knapp

Experimental Facilities Division
Advanced Photon Source
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Abstract

The analytical results and design considerations for a novel cryogenically cooled Advanced Photon Source (APS) monochromator are presented. Because the monochromator uses silicon crystal, cryogenic cooling enables one to take advantage of the high conductivity and low thermal expansion coefficient of silicon at cryogenic temperatures. The APS monochromator features a machined slot with variable thickness below the surface. With this configuration, only a fraction of the total undulator power is absorbed by the crystal; the remaining power is transmitted through the crystal and is absorbed by a second element that can be cooled by standard cooling techniques. A variety of analyses has been performed with different parameters and configurations to maximize the performance of the monochromator and minimize the total absorbed power by the crystal.

Introduction

Knapp [1] proposed a cryogenically cooled monochromator that uses a cut under the monochromator surface. The advantage of such a monochromator would be to reduce the load of the cryogenic cooling system. Wang and Kuzay [2] propose a variable thickness window concept for a synchrotron radiation beamline. The use of a variable thickness window can increase the heat conduction area without increasing the thickness in the core area so that the maximum temperature in the window can be significantly decreased. The structural integrity can be increased in regards to the buckling load in thin windows and the shock due to sudden loss of vacuum.

This paper combines the concepts suggested by Knapp [1] and that of variable thickness [2] and suggests a monochromator with a variable thickness cutting slot under the monochromator surface. As an example of an application of the concept, a APS monochromator design is investigated. The paper will examine different design options and find one that fits the need best. Comparison of uniform thickness, variable thickness, and solid piece of monochromator is presented.

Cryogenically Cooled Monochromator Analyses

The APS Undulator A monochromator is located 30 meters from the source. There is a 2.5 mm X 1.5 mm slit in front of it. Material properties are: Young's modulus E = 130 GPa, fracture stress σ_f = 180 MPa, density ρ = 2.325 g/cm^3, and the thermal expansion coefficient and thermal conductivity are temperature dependent. Boundaries are assumed to be convection cooled with a film coefficient of 2 W/cmK.

<u>Variable thickness monochromator</u>

Figure 1 shows a cross section of the variable thickness monochromator concept and its model used for finite element analysis. The thickness of the crystal is expressed by the form:

$$h(x,y) = a + bx^2 + cy^2 . \qquad (1)$$

Because the monochromator may be operated under any gap size condition and the incident angle is different, as shown in table 1, analysis must be performed for all cases to guarantee the performance of the monochromator. An alternative is to find the worst case and only perform the analysis for the worst case. Then, the performance of all other cases can be guaranteed.

XRAP [3] is a code developed for the purpose of x-ray absorption and variable thickness structure heat transfer and thermal stress analysis. XRAP can do an x-ray absorption analysis and precise heat transfer and thermal stress analysis for two-dimensional structures with temperature-dependent material properties, such as thermal conductivity and thermal expansion coefficient, and with consideration of radiation cooling. When the structure is thick, XRAP can give an average across the thickness. XRAP is used here for a first step screening analysis. The analysis of the monochromator starts with the absorption and heat transfer analysis for all cases in table 1. If a worst case is found, that case is then further analyzed by a three-dimensional finite analyses with a more precise model.

Table 1. The cases analyzed for APS Undulator A monochromator

Case	Gap (mm)	Eff. Field (T)	K	E1 (keV)	θ (degree) [Si(111)]
1	11.5	0.703	2.17	4.21	28.04
2	13.0	0.609	1.88	5.11	22.82
3	15.0	0.504	1.55	6.39	18.05
4	16.0	0.458	1.41	7.06	16.28
5	18.0	0.379	1.17	8.39	13.66
6	20.0	0.313	0.96	9.63	11.88
7	30.0	0.121	0.37	13.19	8.64
8	40.0	0.047	0.14	13.96	8.16

Because the spectral distribution of the X-ray photons is different for different values of the deflection parameter K and for different inciden angles, a series of analyses are performed for eight different K values with three sets of fixed geometry parameters, (i.e., a = 0.5, b = 0.4 and c = 0, a = 0.25, b = 0.4, and c = 0, and a = 0.5 and b = c = 0, in Eq. 1.) to determine the worst case.

The temperature-dependent thermal expansion coefficient and thermal conductivity are from reference [4]. All analyses by XRAP assume that the edges of the monochromator, which is cut into a curved shape (so-called variable thickness), have a temperature of 100 K.

Analysis results are listed in table 2 for the total absorbed power and the maximum temperature on the monochromator.

Table 2. Analysis results for the different monochromators at Bragg angle

K	θ*	$h = 0.25 + 0.4x^2$		$h = 0.5 + 0.4x^2$		$h = 0.5$	
		P_{absorb} (W)	T_{max} (K)	P_{absorb} (W)	T_{max} (K)	P_{absorb} (W)	T_{max} (K)
2.17	28.04	156.2	150.7	179.6	129.5	164.9	157.9
1.88	22.82	166.1	147.1	187.8	127.1	174.6	153.9
1.55	18.05	165.7	131.3	183.4	120.0	173.0	136.9
1.41	16.28	160.9	126.2	176.1	117.0	167.2	129.3
1.17	13.66	149.4	119.8	160.7	113.2	154.4	121.8
0.96	11.88	123.3	111.8	130.1	108.0	126.9	112.7
0.37	8.64	24.3	102.0	24.8	101.5	24.7	102.2
0.14	8.16	0.67	100.2	0.76	100.1	0.76	100.1

* θ is the Bragg angle between beam and crystal (degree)

From table 2, it can be seen that if the monochromator is at the Bragg angle with the x-ray beamline, the worst case occurs when K = 2.17, i.e., when the gap size is the minimum. The maximum temperature for the case with $h = 0.5 + 0.4x^2$ is 129.5 K, and it is in the range of the minimum thermal expansion coefficient. This design is very promising and can potentially be a successful design if all the assumptions (especially that of the edge temperature of the monochromator being 100 K) in the analysis can be met. Because the temperature at the edge of the cutting slot of the monochromator is assumed to be at a fixed temperature, 100 K, a large model including the whole silicon crystal block and its convection boundary should be used to see if this assumption is true.

A three-dimensional finite element analysis using ANSYS [5] then is performed on this worst case. The finite element model is shown in figure 1, in which only one quarter of the monochromator is modeled due to symmetry (not exactly symmetric about x-y plane, but the difference is very small). The parameters used are as follows:

Geometry	
Height	40 mm
Width	81.5 mm
Length	80 mm
Thickness of the cutting	$0.25 + 0.4\,x^2$, $0.5 + 0.4\,x^2$ and 0.5
Convection heat transfer coefficient	2 W/cm^2 K
Bulk temperature	90 K

For the APS monochromator analysis, two layers of a solid element are used to consider the depth effect. Table 3 presents the results for case 1 in table 1 from both a finite element analysis and a finite difference method implemented in XRAP. When the edge temperature in the analyses by XRAP is obtained by corresponding finite element analysis, both approaches give very similar results.

Table 3. Analysis results for the K=2.17 case

Thickness	$0.25 + 0.4\,x^2$		$0.5 + 0.4\,x^2$	
Analysis method	ANSYS	XRAP	ANSYS	XRAP
$P_{absorbed}$(W)	161.92	156	193.4	170.1
T_{bulk} (K)	90	N/A	90	N/A
T_{edge} (K)	108	108	113	113
T_{max} (K)	163.6	163.5	153.3	155.4
θ_x (10^{-6} radian)	N/A	N/A	11.0	N/A
θ_y (10^{-6} radian)	N/A	N/A	1.9	N/A

It can be seen that the edge temperature from finite element analysis is larger than that used in the table 2 in the analysis by XRAP (which was an assumed boundary condition). This means that the design modeled by the finite element method cannot achieve the design goal of 100 K for the edge temperature. We have to improve the design by using a different geometry and better cooling technique for a larger convection coefficient, or, alternatively, use a smaller incident angle. The first choice might be not practical or is limited by the current cooling technique. Using a smaller x-ray incident angle seems to be the first choice.

The investigation then focuses on the same geometry and assumption as above but with a 10-degree x-ray incident angle. The bulk temperature of the coolant is assumed to be 85 K. The thickness of the cutting slot is $h = 0.25 + 0.4x^2$. The total absorbed power is 191.7 W calculated by XRAP. The finite element analysis reveals that the maximum temperature on the monochromator is 122.8 K. As shown in figures 2 and 3, the angular changes in the vertical direction are almost zero in the usable range and those in the horizontal direction are about 1.2 micron radian, all within user's tolerance. Again, when using the edge temperature from the finite element analysis, 103.5 K, XRAP determines the maximum temperature of the monochromator to be 124.2 K. The results from both approaches are very close.

It can also be seen from tables 1 and 2, if all the conditions are the same, the thicker the monochromator, the lower the maximum temperature. There will always be some trade-offs between using thick and thin cut monochromator. A thicker monochromator is easier to manufacture than a thin one. But a thicker one has a larger absorbed power that must be handled by the cryogenic cooling system. The extreme is to use a solid block monochromator that certainly has a better performance than that of a cutting slot monochromator. But, in that case, the cryogenic cooling system has to handle all the incident x-ray power.

Uniform thickness monochromator

Analyses are performed on both a uniform thickness monochromator and a variable thickness monochromator. The same assumptions are used here as for the previous section. Table 4 lists the results of three cases: one variable thickness monochromator and two uniform thickness monochromators. In table 4, the parameter K is the device deflection parameter, α is the inclined angle of beam on to the monochromator surface, and h is the thickness of cutting monochromator.

Table 4. Comparison of results of uniform thicknesses and variable thickness monochromators

K	α	$h = 0.25 + 0.4x^2$		$h = 0.25$		$h = 0.5$	
		P_{absorb} (W)	T_{max} (K)	P_{absorb} (W)	T_{max} (K)	P_{absorb} (W)	T_{max} (K)
2.17	85	230.7	110.0	211.9	122.5	238.3	110.8
1.88	80	199.9	119.8	178.6	158.7	208.3	122.3

From the table, one can see that, by using a variable thickness monochromator, the temperature increment of the monochromator can be significantly decreased while not increasing the total absorbed power very much. For example, in the case of K=1.88, the maximum temperature increment of the variable thickness is 19.8 K and that of uniform thickness monochromator (h = 0.25) is 58.7 K, an almost 300 percent improvement. However, the total absorbed power is 199.9 W versus 178.6 W, only a 12 percent increment.

Compton Scattering Effect

The difference in the total absorbed power with consideration of the Compton scattering effect and that without consideration of Compton scattering is within three percent.

Discussion

The analyses show that the deformation of the monochromator at the beam footprint is negative. This suggests that one can adjust the coolant temperature (or equivalent) so that the maximum temperature is in the range of 120 - 125 K, in which the monochromator has the best performance (least angle change). When designing the cooling system of a monochromator, one can control the maximum temperature of the silicon crystal at 120 to 125 K, in which range the thermal expansion coefficient is minimum.

A solid piece monochromator will give the best performance if the cryogenic cooling system can handle the total power of the beamline. This value from a 2.5 mm X 1.5 mm slit can be as large as 300 to 400 watts. The variable-thickness cryogenically cooled monochromator can satisfies the performance requirement of the monochromator while the absorbed power is low.

Conclusion

A cryogenically cooled, variable-thickness monochromator with $h = 0.25 + 0.4x^2$, which has an incident angle of 10 degrees with the x-ray beamline, can guarantee small algular changes under the APS Undulator A power. The total absorbed power in the monochromator is 190 watts, which would need to be handled by the cryogenic system.

Acknowledgment

The authors would like to express thanks to S. Picologlou for editing this paper. This work is supported by the U.S. Department of Energy, BES-Materials Sciences, under contract no. W-31-109-ENG-38.

References

[1]. G. K. Knapp, Private communication.

[2]. Z. B. Wang and T. M. Kuzay, A Variable Thickness Window: Thermal and Structural Analyses, to be presented in SRI '94.

[7]. Z. B. Wang, X-Ray Optical Element Analyses and X-Ray Absorption Package (XRAP), M.Sc Thesis, May 1994, Computer Science Department, IIT.

[5]. B. X. Yang, M. Meron, Y. Ruan, and W. Schildkamp, Performance analysis of cryogenic silicon Laue monochromators at APS undulator, SPIE Proceedings, Vol 1997, 1993.

[4]. ANSYS User's Manual, Swanson Analysis Systems, Inc.

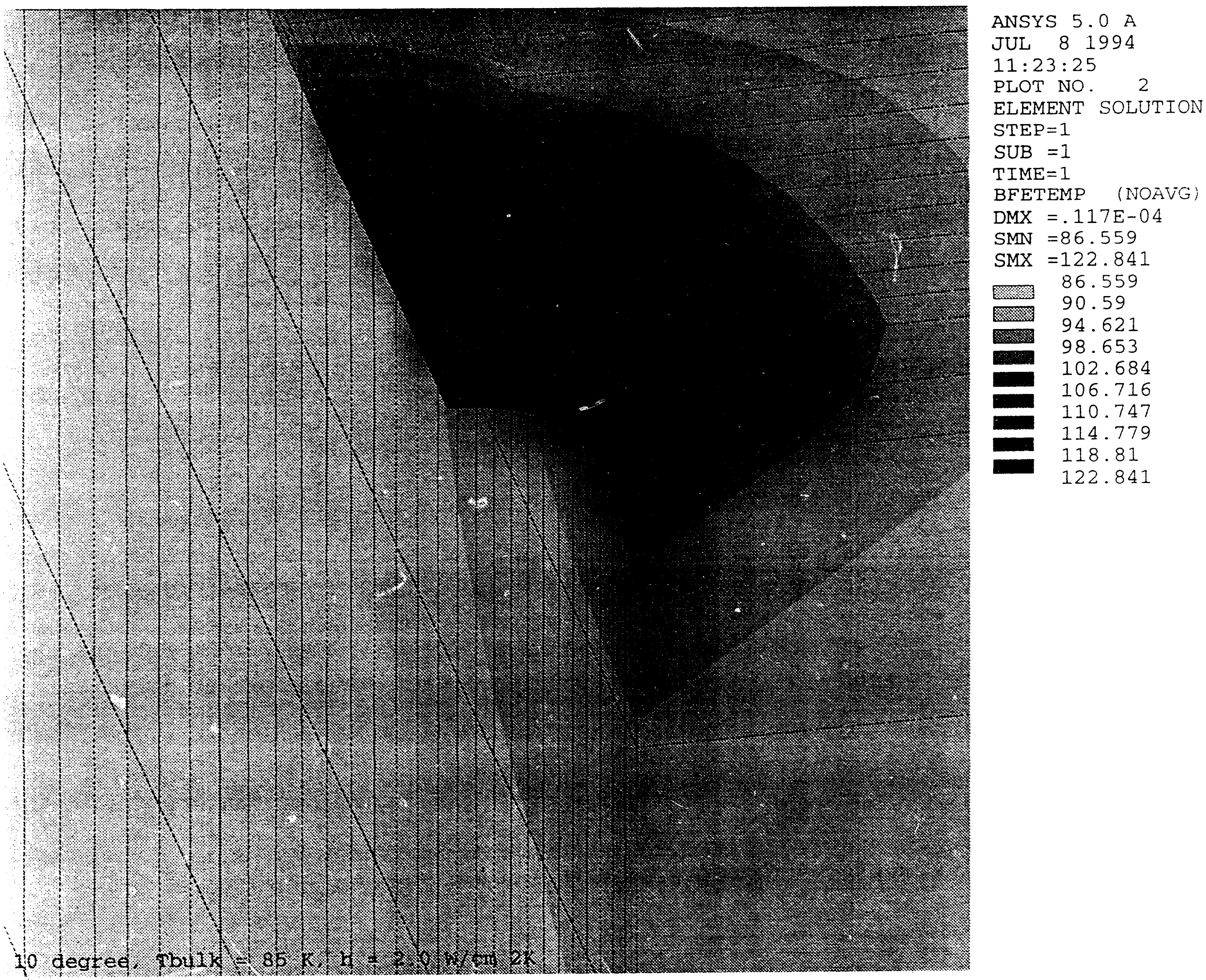

Figure 1. Finite Element Model of APS Monochromator and Temperature Distribution

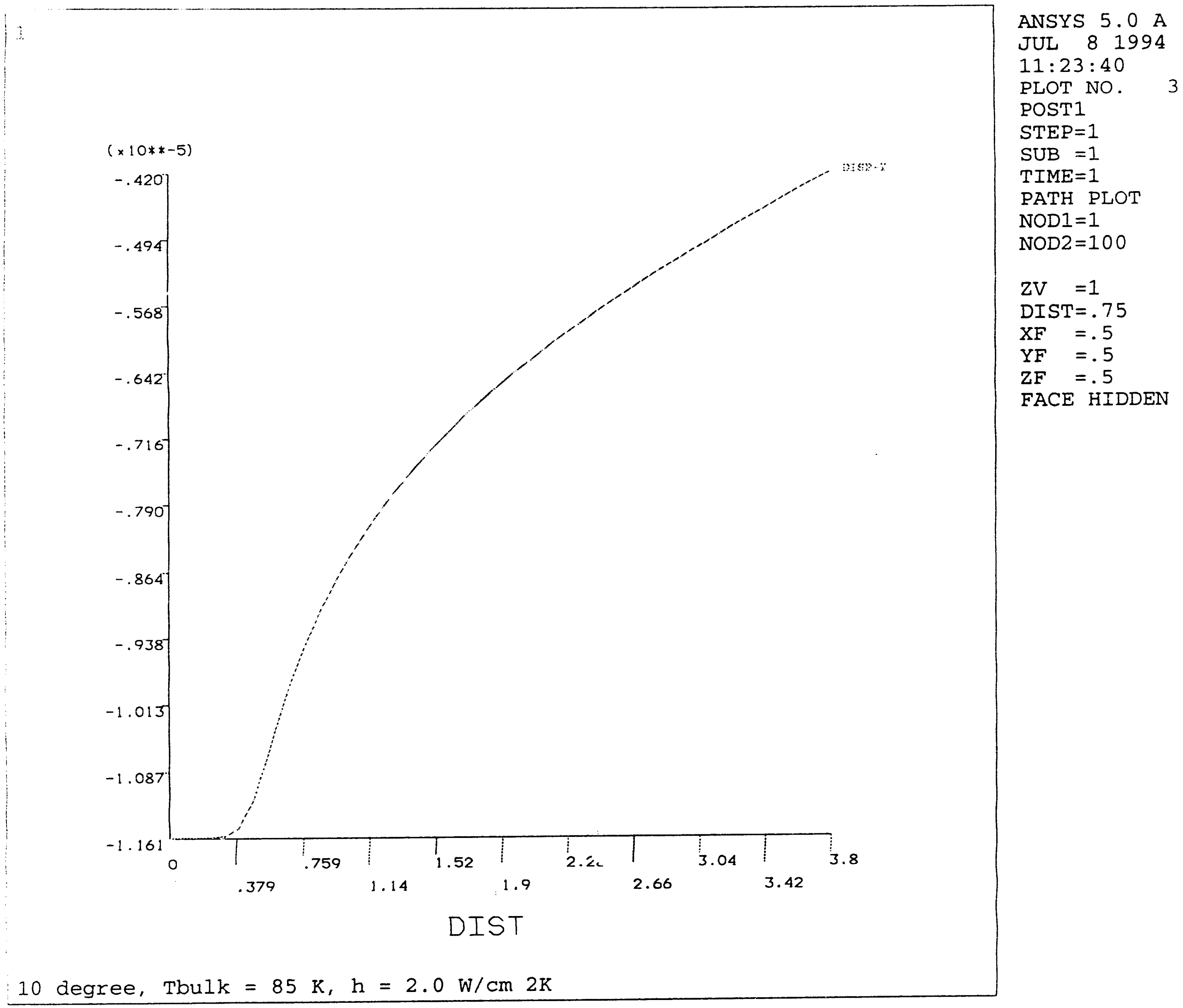

Figure 2. Displacement of Monochromator in the Vertical Direction

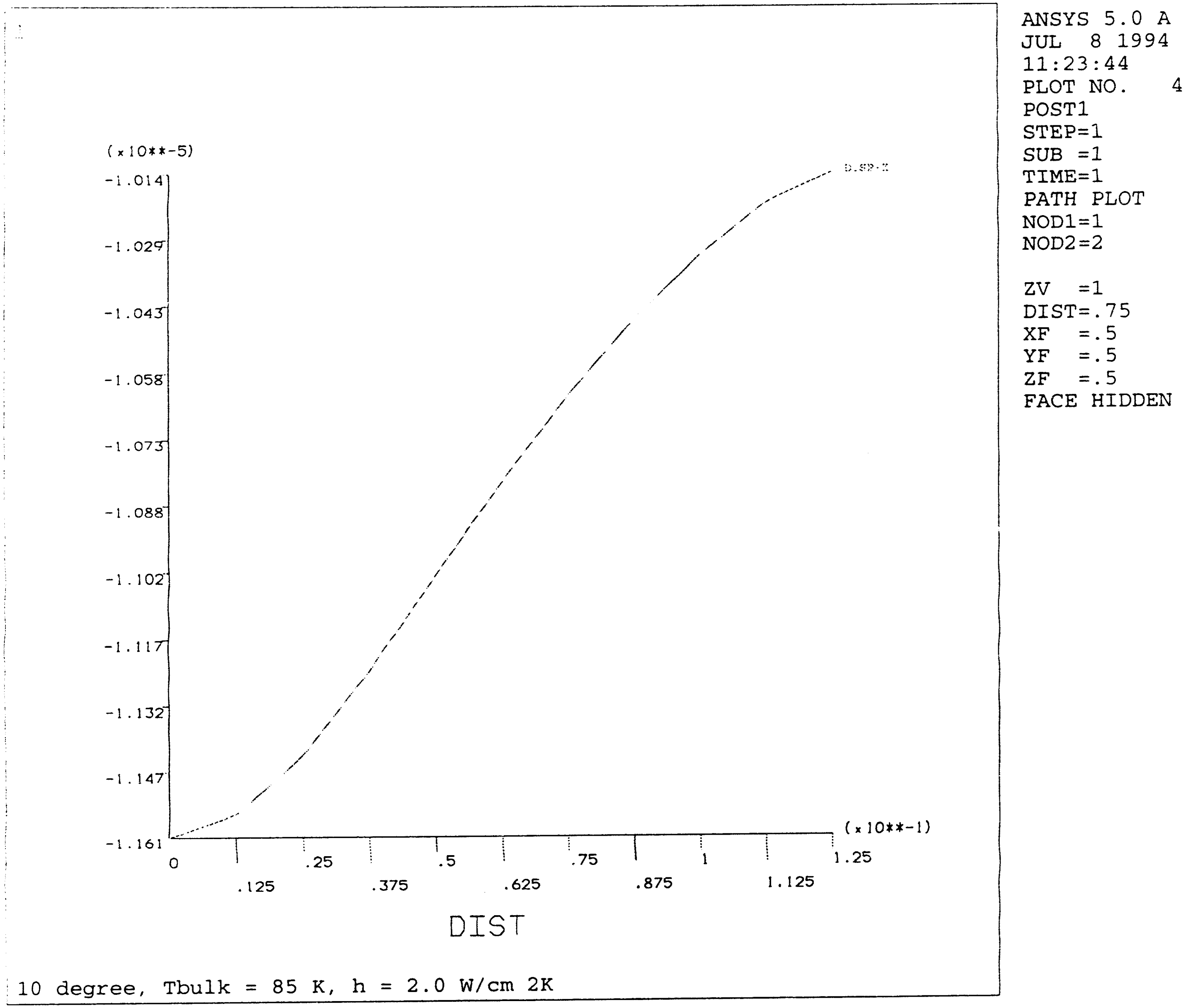

Figure 3. Displacement of Monochromator in the Horizontal Direction

DATE
FILMED
10/ 4 / 94

END