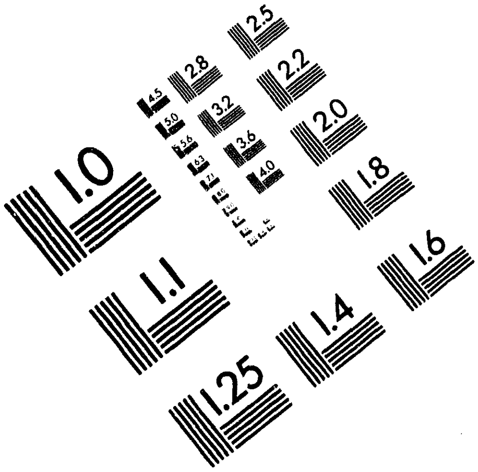

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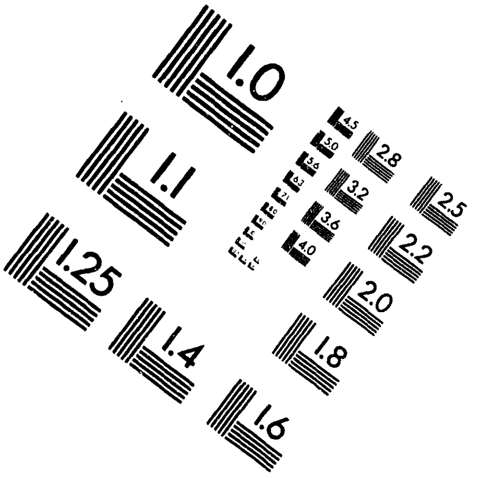

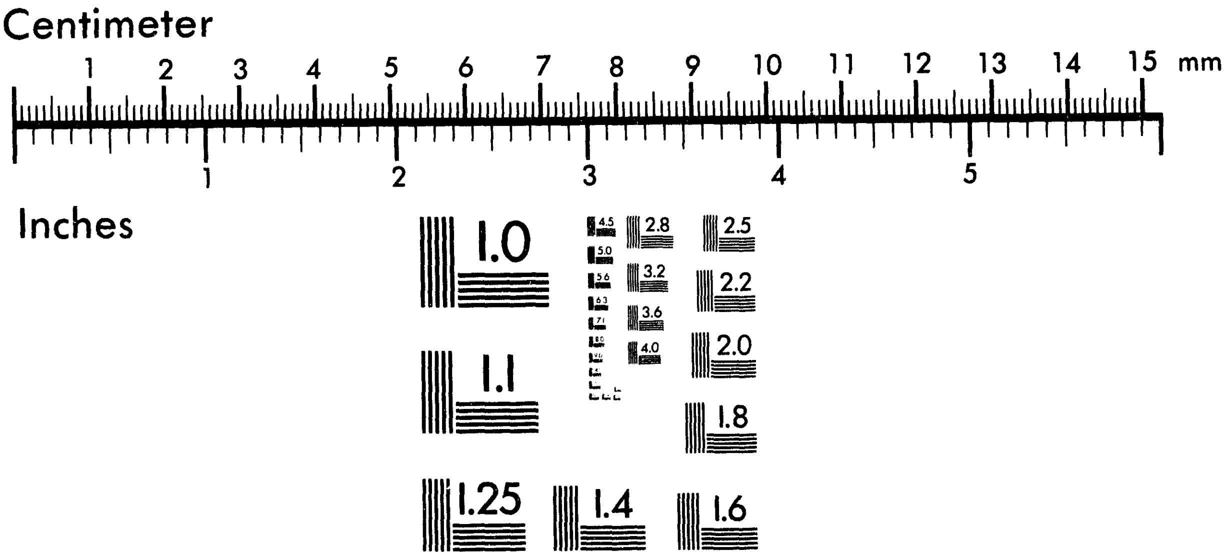

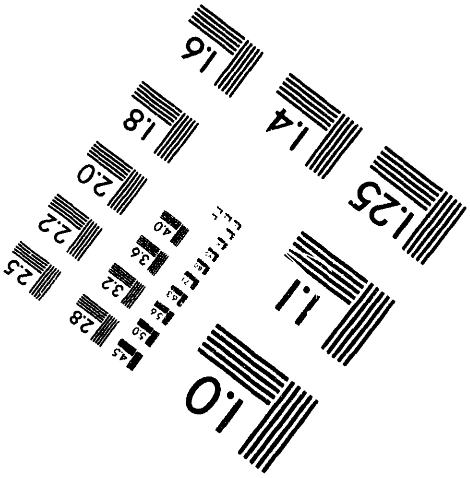

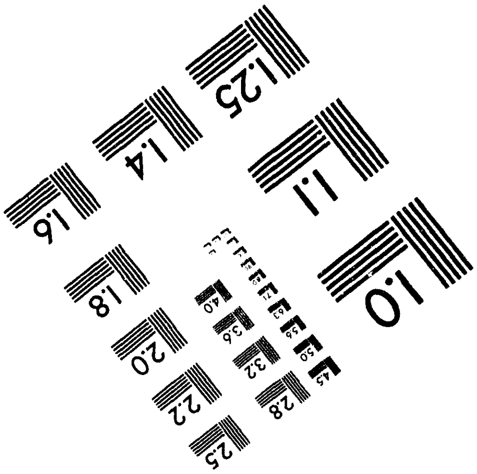

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Design and Thermal Stress Analysis of High Power X-ray Monochromators Cooled with Liquid Nitrogen.*

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Design and thermal stress analysis of high power x-ray monochromators cooled with liquid nitrogen

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Cryogenically cooled, single-crystal silicon, x-ray monochromators offer much better thermal performance than room-temperature silicon monochromators. The improved performance can be quantified by a figure-of-merit equal to the ratio of the thermal conductivity to the coefficient of thermal expansion. This ratio increases by about a factor of 50 as the temperature is decreased from 300 K to 100 K. An extensive thermal and structural finite element analysis is presented for an inclined, liquid-nitrogen-cooled, Si monochromator crystal diffracting 4.2 keV photons from the [111] planes using Undulator A at the Advanced Photon Source. The angular size of the beam accepted on the crystal was chosen to be 50 μrad vertically and 120 μrad horizontally. The deflection parameter, K, was 2.17 for all cases. The peak power density at normal incidence to the beam was calculated to be 139 W/mm^2, and the total power was 750 W at a distance of 30 m from the source for a positron current of 100 mA. The crystal was oriented in the inclined geometry with an inclination angle of 85° for all cases. The performance of the crystal was investigated for beam currents of 100, 200, and 300 mA. The calculated peak slopes of the diffraction plane over the extent of the beam footprint were -1.17, -2.35, and 0.33 μrad, and the peak temperatures were 88.2, 102.6, and 121.4 K, respectively. The variation in the Bragg angle due to change in d-spacing across the beam footprint was less than 1 μrad for all cases. These results indicate that a properly designed, cryogenically cooled, inclined silicon monochromator can deliver the full brilliance of Undulator A at even the highest machine currents.

I. INTRODUCTION

The use of cryogenically cooled, single-crystal optics for high-heat-flux undulators is gaining wide spread interest in the synchrotron radiation community. Bilderback first pointed out the potential for cryogenically cooled, synchrotron radiation optical components in 1986.[1] In order to take advantage of the full brilliance of the x-ray beams at the APS, the thermo-mechanical strain in the monochromator crystal must be much smaller than the intrinsic reflection width of the crystal. For example, the Bragg reflection width for Si [111] at 4.2 keV is 70.6 μrad. An aggressive research program has been mounted at the APS to develop cryogenically cooled optics.[2]

This paper presents a series of finite element analyses of an inclined, cryogenically cooled Si monochromator for use with APS Undulator A. The undulator characteristics can be found in Ref. 3. The inclined reflection geometry is a novel method of spreading out the footprint of the beam while preserving symmetric diffraction.[4] At an inclination angle of 85°, the peak heat flux is reduced by an additional factor of 11.5 compared to the standard Bragg geometry. Cryogencially cooled optics lend themselves very well to the inclined geometry. Due to the increased thermal conductivity, the cooling channels can be placed much further from the diffraction surface than can be done with water or liquid- metal cooling. This allows for easier construction of high efficiency, heat exchanger configurations without adversely impacting the diffraction surface. Also, the larger volume of the crystal can be used to transport the heat, thereby reducing the heat flux at the fluid interface and alleviating the possibility of boiling.

Work has been done recently to show how a cryogenically cooled crystal operating in the standard Bragg geometry can work for Undulator A at 100 mA.[5] In this work, the x-rays are set to diffract from a thin section, about 0.6 mm thick, of the crystal. This type of crystal is especially suited for low energies where most of the high energy photons pass through without being absorbed. Use of a thin, partially absorbing crystal decreases the local heat flux and total absorbed power. This method is highly geometry dependent. The thin section must be no wider than the beam footprint. Increasing the thermal path length unnecessarily causes the temperature to rise rapidly.

II. THERMAL MODELING

The monochromator crystal was modeled as a simple block cooled from the bottom surface. The crystal was 50 mm wide, 10 mm thick, and 90 mm long. This size was chosen so that the inclined beam footprint at 4.2 keV would fit on the crystal. For higher energies, the crystal would necessarily be longer if all other parameters are held constant. However, much can be done by changing the size of the accepted beam or using different inclination angles. For example, a 190 mm x 25 mm Si [111] monochromator inclined at 85° and accepting a beam 1.5 mm x 1.5 mm could scan to 20 keV.

The beam size normal to the crystal was 1.5 mm vertically and 3.6 mm horizontally. This size includes the entire 1st harmonic in the central cone of radiation from the undulator. A uniform heat transfer coefficient of 5 W/cm^2 °C was applied to the bottom surface. This value is readily obtainable by using porous-media-enhanced cooling.[6] The bulk nitrogen temperature was 77 K. The heat load was applied as a surface heat flux. The incidence angle was 2.35° to the plane of the crystal surface. Because the incidence angle is so small, the assumption of absorption at the surface is adequate. The thermal conductivity and coefficient of thermal expansion were treated as temperature dependent properties.

Five cases were modeled. The crystal performance was simulated for positron currents of 100, 200, and 300 mA. In addition, the effect of doubling the heat transfer coefficient to 10 W/cm^2 °C for the 300 mA case was investigated. The effect of doubling the crystal thickness to 20 mm at 300 mA was also modeled. For the structural analysis, a symmetry boundary condition was imposed on the central plane, and the central node under the peak heat flux was held fixed. The rest of the crystal was unconstrained.

III. RESULTS AND DISCUSSION

A contour plot of the temperature profile for the 300 mA case is shown in Fig. 1. The minimum temperature is about 81 K. Note that the heat is diffusing quite readily throughout the entire crystal. Because the thermal conductivity is so large, the coolant can be placed much further from the heated surface than for a room-temperature crystal. Therefore, the peak local heat flux at the fluid interface is much reduced alleviating the problem of boiling and critical heat flux. The surface temperatures along the central axis of the crystal for the 100, 200, and 300 mA cases are shown in Fig. 2. The peak temperatures are 88.2, 102.6, and 121.4 K, respectively. The temperature difference on the surface across the beam footprint in the beam direction was about 1.5, 4.0 and 8.0 K, respectively. The peak temperature increases nonlinearly as the current is increased because the thermal conductivity is decreasing. However, it should be remembered that the expansion coefficient approaches zero as the temperature nears about 125 K. The effect of doubling the heat transfer coefficient to 10 W/cm^2 °C and the effect of doubling the crystal thickness to 20 mm for the 300 mA case are shown in Fig. 3. Doubling the thickness caused the peak temperature to increase by about 4 K. This is a relatively small amount indicating that the coolant can be placed relatively distant from the diffraction surface without paying a high penalty in temperature increase. The added thickness allows the heat to diffuse more, thereby, decreasing the interfacial heat flux. The added thickness also allows a larger coolant pressure to be used without causing pressure related strain at the diffraction surface. Doubling the heat transfer coefficient caused the peak temperature to decrease by about 8 K. This result indicates that much can still be gained by increasing the heat transfer coefficient. Because the Si conductivity is so large, the heat transfer is convection limited.

The slope and displacement of the diffraction planes along the central axis of the crystal at 100, 200, and 300 mA are shown in Figs. 4, 5, and 6, respectively. The variation in Bragg angle is given by

$$\Delta\theta_B = slope + \frac{\Delta d}{d} tan\theta_B << \Delta\theta_0$$

where *slope* is the thermal slope error, *d* is the spacing between the crystalline planes, and $\Delta\theta_0$ is the Darwin width of the crystal. This equation shows that the total variation in the Bragg angle must be much less than the intrinsic reflection width. The peak slopes under the footprint of the beam were -1.17, -2.35, and 0.33 μrad for these cases. The variation in Bragg angle due to change in d-spacing was -0.4, -0.8, and -0.9 μrad, respectively. At 100 and 200 mA, the surface normal displacement was found to be concave due to the negative thermal expansion coefficient below about 125 K resulting in a "thermal dimple". At 300 mA, a small "thermal bump" was present at the hottest part of the beam footprint superimposed on an overall "thermal dimple". In this region, the thermal expansion coefficient is beginning to become positive. The exact temperature where the expansion coefficient zero crossing occurs was about 120 K due to interpolation. This leads to the interesting result that the slope error at 300 mA is less than that at 100 or 200 mA. This phenomenon in principle allows one to match the inclination angle to the particular experimental situation so as to cause the peak temperature to be around 125 K resulting in minimal distortion of the diffraction planes. For the analysis in question, if one is operating at 100 mA, only about 1/3 of the spreading of the 85° case is required, i.e., an inclination angle of approximately 75°. This would allow for smaller crystals and easier alignment due to the larger incidence angle. The thermal error of the Bragg angle was much less than the Darwin width for all of the cases.

IV. SUMMARY

It has been shown that an inclined, cryogenically cooled, Si monochromator can handle the APS Undulator A beam with minimal distortion up to a positron current of 300 mA. The inclination angle can be tailored so that, for a given set of machine parameters, the crystal performance is optimized. In distinction to room-temperature crystals, cryogenic crystals are not limited in their heat transfer performance by the material properties. The primary limiting factor for liquid-nitrogen cooled crystals is the relatively low heat flux required for onset of nucleate boiling and critical heat flux. The dominant resistance to heat flow is convection resistance. This indicates that continued improvement in performance can be attained by applying various enhancement techniques, such as, porous media.

ACKNOWLEDGMENTS

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[6]C. S. Rogers, Proc. Soc. of Photo-Optical Instrum. Eng., **1997**, 236, (1993).

FIGURE CAPTIONS

FIG. 1. Temperature contour plot of inclined crystal for Undulator A at 300 mA, crystal thickness, t=10 mm, heat transfer coefficient, h=5 W/cm^2 °C.

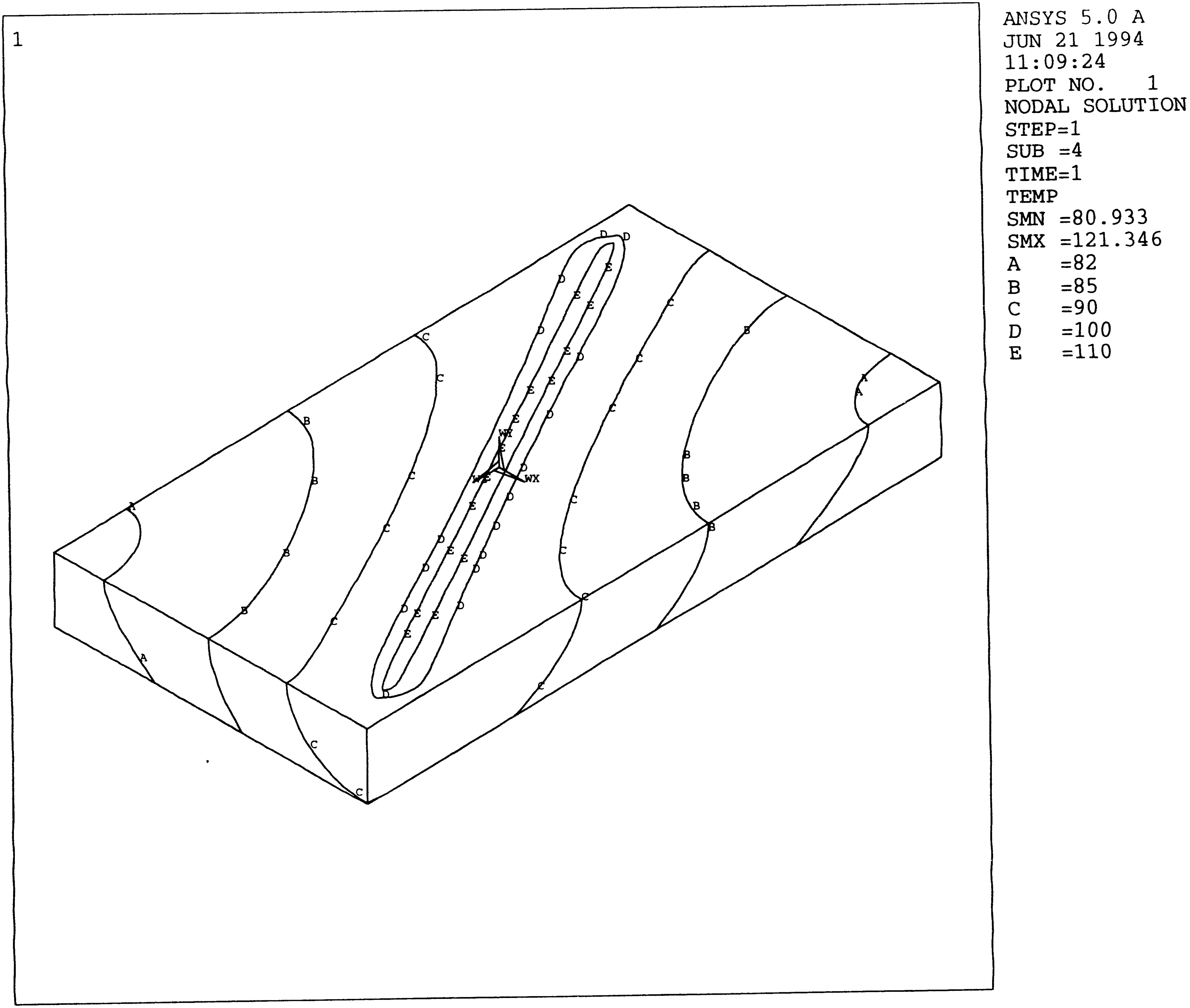
FIG. 2. Surface temperature profile along central axis of crystal (see Fig. 1) for Undulator A at 100, 200, and 300 mA.

FIG. 3. Comparison of surface temperature profile along central axis of crystal at 300 mA when thickness is increased to 20 mm and when heat transfer coefficient is increased to 10 W/cm^2 °C.

FIG. 4. Displacement and slope of diffraction plane along central axis of inclined crystal for 100 mA current, crystal thickness, t=10 mm, heat transfer coefficient, h=5 W/cm^2 °C.

FIG. 5. Displacement and slope of diffraction plane along central axis of inclined crystal for 200 mA current, crystal thickness, t=10 mm, heat transfer coefficient, h=5 W/cm^2 °C.

FIG. 6. Displacement and slope of diffraction plane along central axis of inclined crystal for 300 mA current, crystal thickness, t=10 mm, heat transfer coefficient, h=5 W/cm^2 °C.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JUN 21 1994
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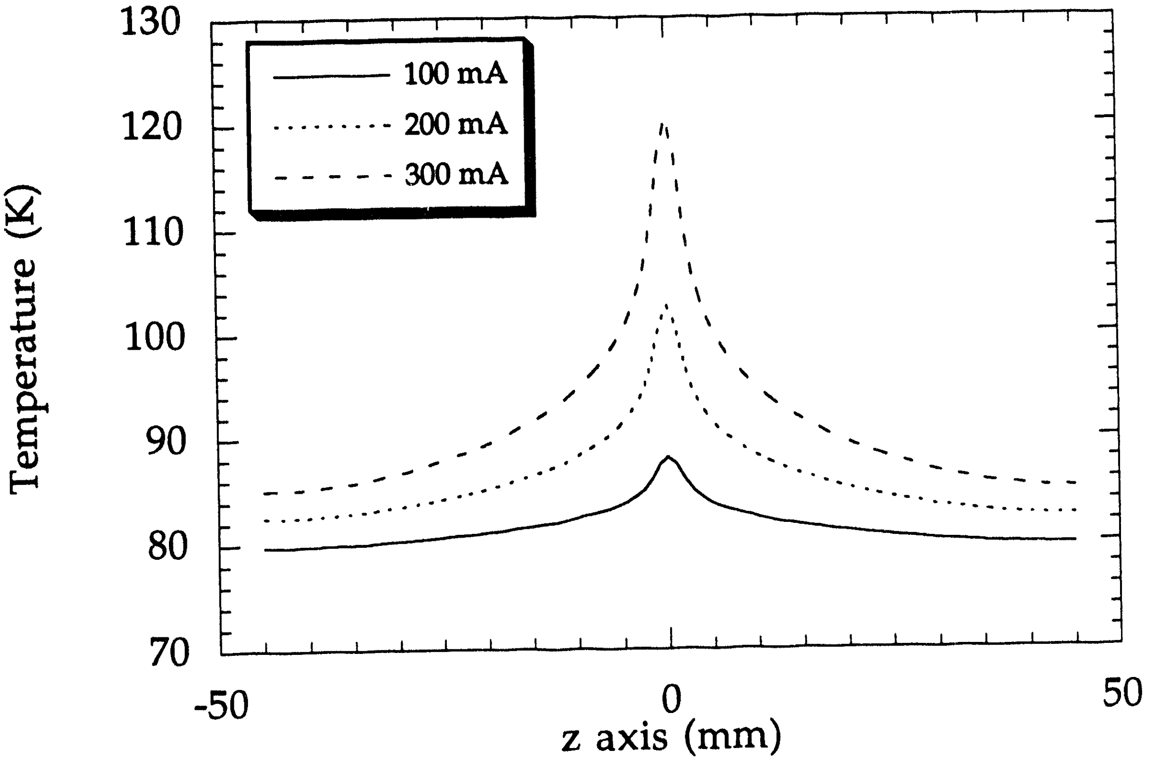
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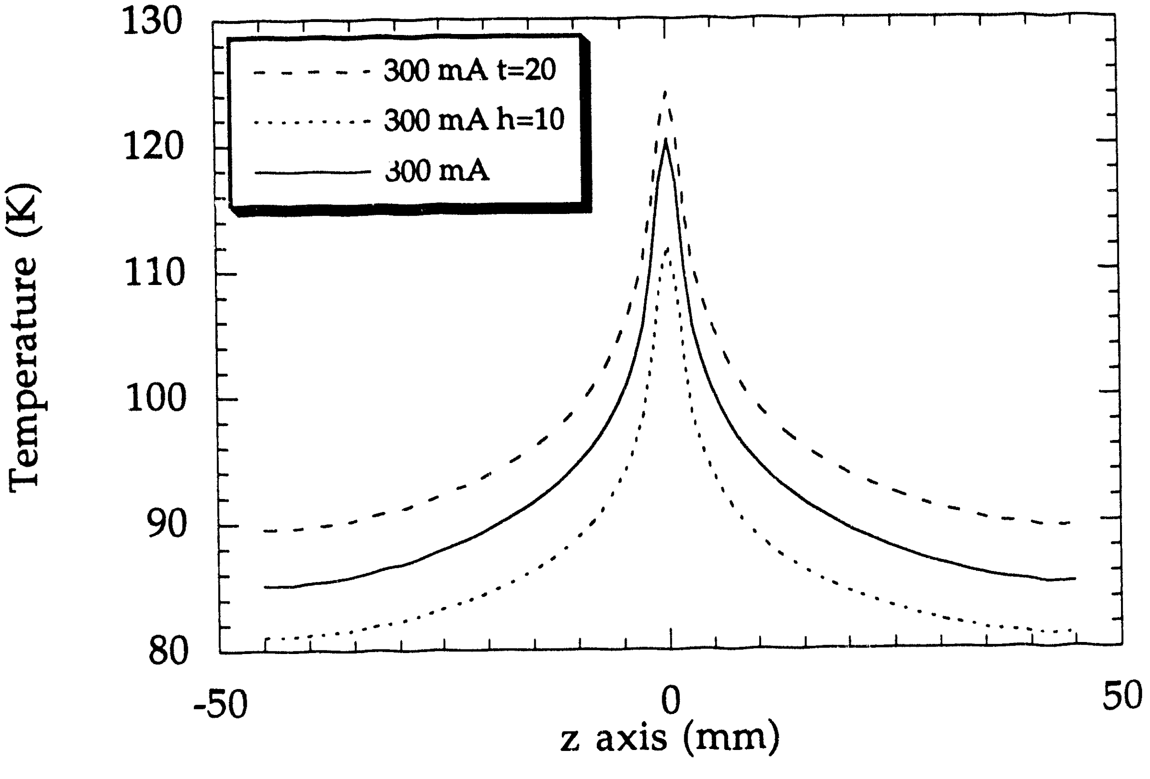
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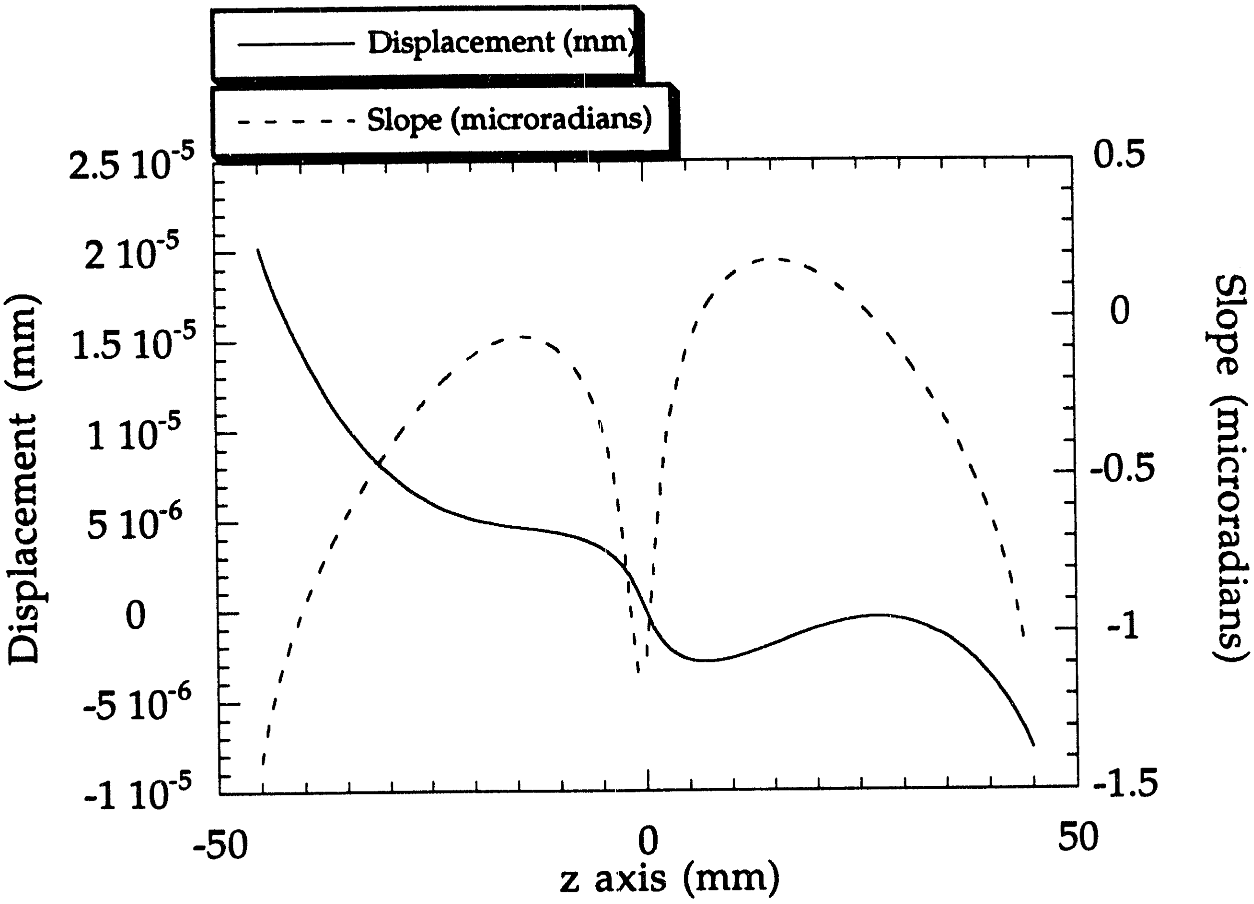
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5 10^-6
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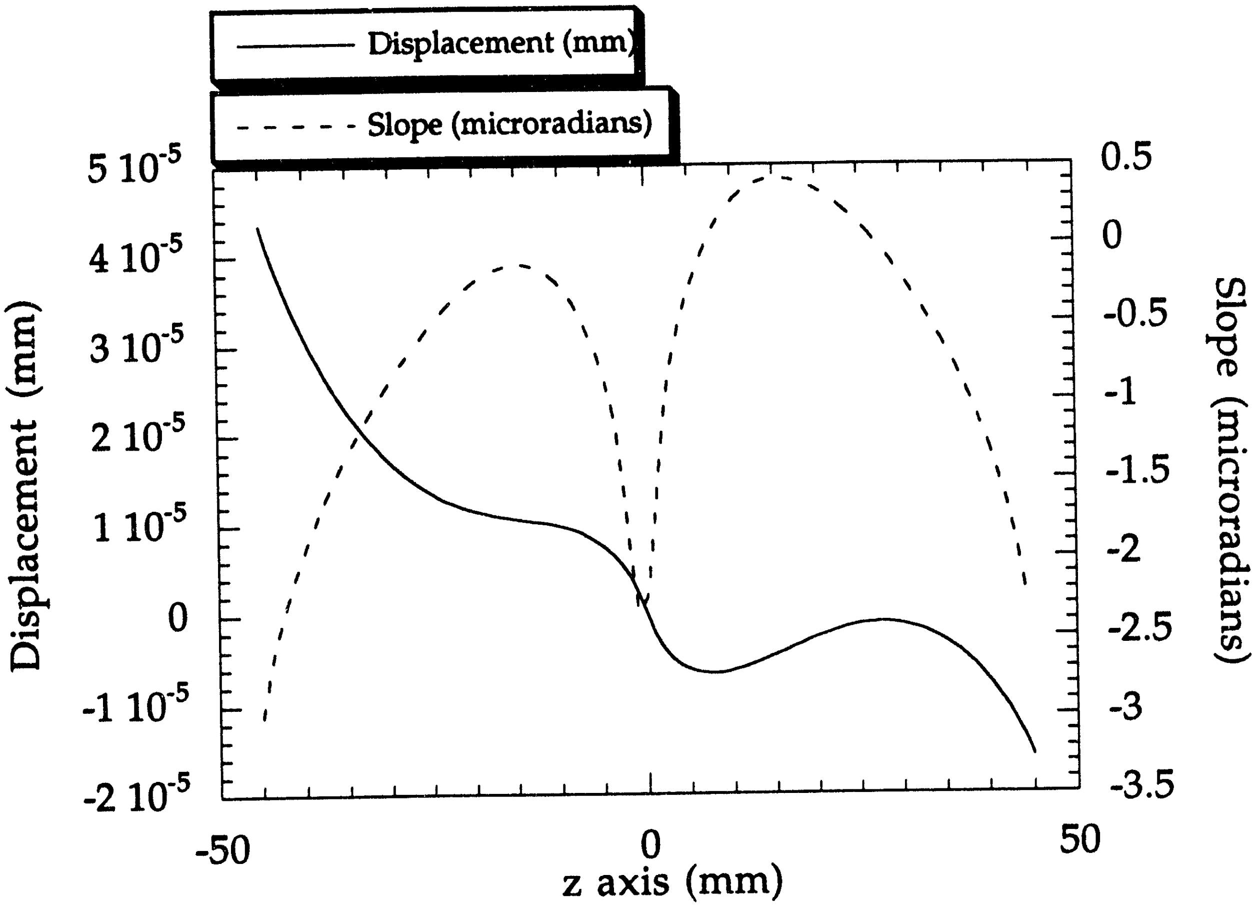
z axis (mm)



Displacement (mm)
Slope (microradians)
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4 10^-5
3 10^-5
2 10^-5
1 10^-5
0
-1 10^-5
-2 10^-5
Displacement (mm)
0.5
0
-0.5
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-2
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-3
-3.5
Slope (microradians)
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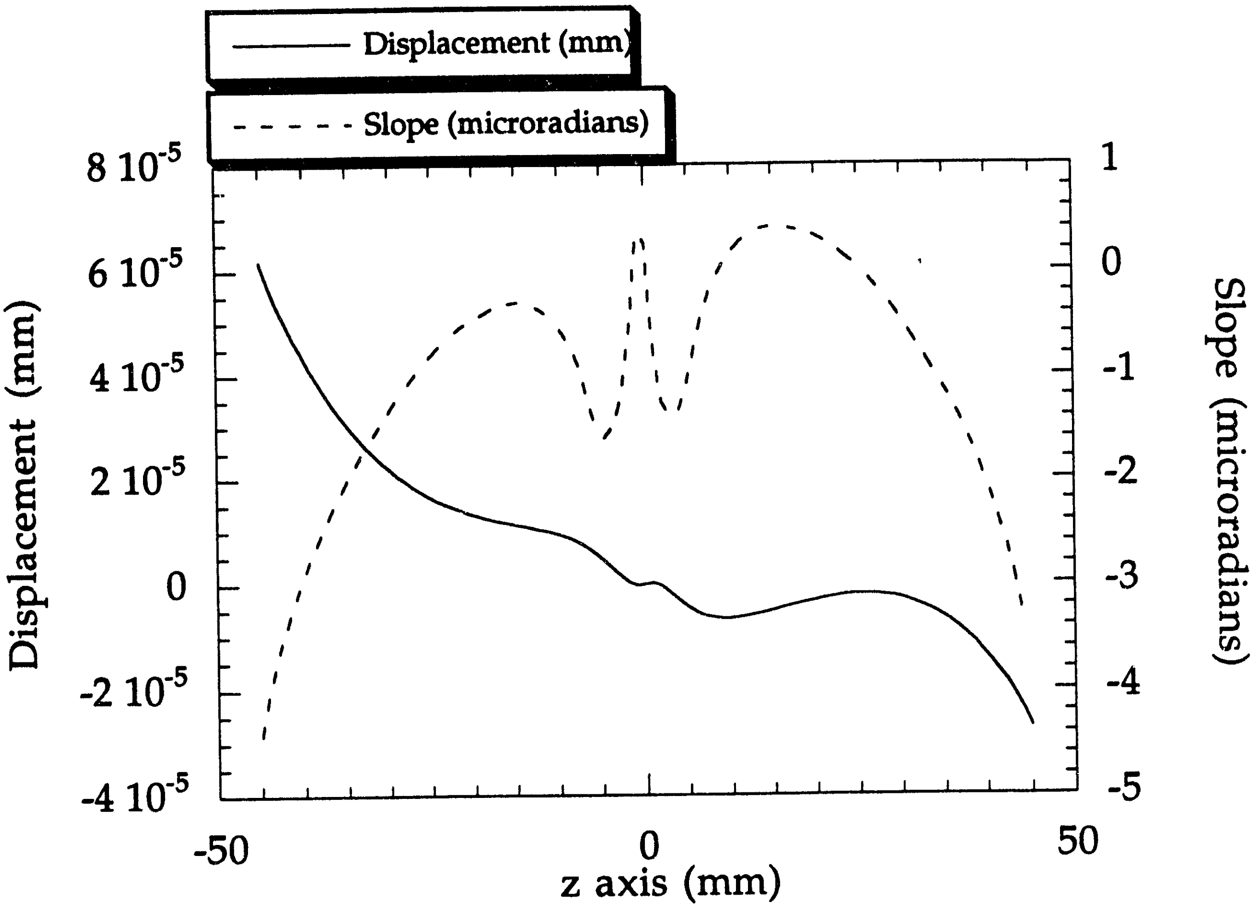
0
50
z axis (mm)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4 10^-5
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0
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-4 10^-5
Displacement (mm)
1
0
-1
-2
-3
-4
-5
Slope (microradians)
-50
0
50
z axis (mm)