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MODELING THE PERFORMANCE OF WATER AND LIQUID GALLIUM COOLED X-RAY OPTICAL COMPONENTS A COMPARISON WITH EXPERIMENT (*)

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Modeling the Performance of Water and Liquid Gallium Cooled X-ray Optical Components- A Comparison with Experiment*

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Abstract:

Thermal and structural analyses of a water or liquid gallium cooled silicon crystal x-ray monochromator subjected to high heat loads have been carried out using a finite element method. From the computed strain distributions in the crystal rocking curves were produced and compared with experimentally measured rocking curves. Good agreement between the general width and shape of the calculated and measured rocking curve profiles was obtained. This initial agreement between calculation and measurement provides the foundation for the extension of our modeling to the prediction of x-ray optical component performance with more complex cooling schemes. Such elaborate cooling techniques may be required for the increased power loadings that will be produced by insertion devices in the next generation of low emittance storage ring sources such as the Advanced Photon Source (APS) to be constructed at Argonne National Laboratory.

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Introduction:

The next generation synchrotron radiation sources being, such as the European Synchrotron Radiation Facility (ESRF) in Grenoble, France and the Advanced Photon Source (APS) at Argonne National Laboratory, Argonne, Illinois are low emittance, insertion device (ID) based radiation sources. These new, high brilliance sources will have wigglers and undulators capable of producing x-rays beams with total powers exceeding 10 kwatts and power densities in excess of 350 watts/mm^2 (at 30 meters from the source at normal incidence) (1) . Effective cooling of x-ray optical components will be imperative for successful operation of these facilities. In order to evaluate and optimize various cooling schemes, a reliable modeling capability for determining optical component performance is essential. This paper describes the current efforts at the APS towards that goal.

Water cooling is now the most common method for the removal of heat from x-ray optical components. An alternative approache pioneered at the APS is the use of liquid gallium as a coolant(2) for x-ray optical components. Liquid metals offer a considerable improvement in cooling efficiency over water because of their thermal and physical properties. Liquid gallium is particularly attractive because of its low vapor pressure, an important consideration in high vacuum environments should coolant leaks occur.

A series of experiments were conducted in collaboration with the Cornell High Energy Synchrotron Source (CHESS) and the National Synchrotron Light Source (NSLS) at CHESS on the 6-pole wiggler to compare the performance of water and liquid gallium cooled monochromators with various cooling channel geometries. A summary of those experiments(3) and a detailed thermal and structural analysis of the monochromators have been previously reported(4). This manuscript reports the recent efforts at modeling the performance of both water and liquid gallium cooled monochromators via the calculation of rocking curves. The calculated rocking curve profiles are very sensitive to the details of the thermal distortions of the crystals as determined by our finite element analysis. The comparison between experimental and calculated rocking curve profiles provides an essential check on the accuracy of the modeling and calculations.

Modeling:

The goal of our modeling studies is to test a variety of cooling design concepts and to optimize performance of x-ray optical component under the influence of high power loads from IDs. This task can be acheived by minimizing the component's thermal distortions by optimization of component geometry for a particular coolant choice. An important performance measure of a perfect crystal monochromator subjected to heat loads is its resulting rocking curve profile. Therefore the initial aim of our modeling program is to obtain a calculated rocking curve profile for a thermally distorted crystal. The is accomplished in a four step process. First, the x-ray absorption profile as a function of depth in the crystal is calculated using the PHOTON(5) program. (While this profile is a calculated quantity, total power incident on the crystal is measured experimentally.) From the power depostion distribution, the thermal profile in the crystal is evaluated and the corresponding thermal distortions are calculated using a finite element analysis. The last step in the four step process is the calculation of rocking curves of the distorted crystal. The emphasis of the modeling effort to date has been on the highest available experimental incident power loadings (≥400 watts) since the experimental rocking curves collected at these powers show the greatest distortions from prefect crystal rocking curve profiles and therefore should provide the most informative comparisons with the calculations.

The geometry of the crystal used in the experiments is shown in Fig. 1. and the meshing scheme used in the finite element thermal/stress *anaylsis is shown in Fig. 2.* Note that half of the crystal is modeled. It's often adequate to model only one quarter of the crystal subjected to synchrotron radiation, however, the low angle of incidence used in the present study combined with the deep penetration of the x-rays due to the high critical energy of the wiggler causes a skewed power deposition along the beam direction. (The ramifications of the skewed power distribution on the calculated rocking curves will he discussed later.) The heat transfer coefficients used in the computations were 5.0 and 0.59 watts/cm^2-K for liquid gallium (@45^o C) and water (@18^o C) respectively, corresponding to flow rates of 0.67 gal/min for gallium and 1.1 gal/min for water. Additional parameters used in the analysis are given in Table I.

<u>Table I</u>

Thermal conductivity (@20° C)	1.256 W/cm-K
Coeff. of thermal expansion	2.4x10^{-6} /K
Modulus of elasticity	11.3x10^{10} Pa
Poisson's ratio	0.3

Calculated thermal profiles, distortions and corresponding slope errors are shown in Figs. 3 and 4.

Reflectivity calculations for the distorted monochromator are made using the dynamical diffraction theory for perfect crystals. In these calculations it was assumed that there were no gradients in the d-spacing, rather all the contributions to the broadening of the reflectivity versus angle profiles were due to slope errors arising from thermal distortions. This assumption is warrented considering that the maximum temperature difference throughout the crystal is less than that required to change the Bragg angle by a Darwin width. This assumption was also supported experimentally where a narrow vertical slit was placed between the second crystal and the detector and the second crystal was rocked. The measured width of the resulting intensity versus and angle curve was very nearly that expected from two perfect crystals, indicating that the small portion of the crystal from which these rays were being diffracted was behaving very much like a perfect crystal. The area under the reflectivity profiles for the strained crystals is constrained to be equal to the area under a perfect crystal reflectivity curve. (A linear relationship between the area under the rocking curve and the stored beam current was observed experimentally, lending support to this approach.)

Rocking curves are then produced by convoluting the reflectivity profile of the distorted crystal with that of a perfect (second) crystal reflectivity curve. The rocking curves shown are the average of several rocking curves taken across the face of the crystal since the slope errors vary in the x-direction (See Fig. 1). The calculated rocking curves for the gallium and water-cooled crystals with the distortions shown in Fig. 4 are plotted in Fig. 5.

Experimental Data:

The experiments were performed using radiation produced from the 6-pole electromagnetic wiggler on the A-line at CHESS. With a stored beam energy of 5.44 Gev, the wiggler has a critical energy of 29 kev. The first crystal of the double crystal monochromator was located 14.5 meters from the source. The normal incidence dimensions of the x-ray beam was 28 mm horizontally (uniform distribution) and 1.7mm full width at half maximum (FWHM) vertically (non-uniform distribution). The measured incident power within this area from the 6-pole wiggler was 7.18 Watts/milliampere. A symmetrically cut Si (111) crystal set to diffract 20 kev x-rays ($\theta_B = 5.67^o$) was used in the experiment. The beam footprint on the crystal was 28 mm (perpendicular to the scattering plane) by 17 mm FWHM (in the scattering plane). The size and geometry of the first crystal is shown in Fig. 1.

Rocking curve measurements at low currents (<5 ma) showed the intrinic perfect crystal widths of ~4 arc seconds for both water and liquid gallium cooling. As the beam current is increased, rocking curves show a clear broadening; the water cooled crystal showing a markedly larger increase in rocking curve width as compared to the gallium cooled crystal. The rocking curve profiles taken at nearly identical incident power for water and gallium cooled crystals are shown in Fig. 6.

For an ideal optical system, the peak output flux should vary linearly with stored beam current. Such a linear relationship between current and count rate is not experimentally observed. Rather, the peak count rate is found to saturate at the 15-20 ma value for the water cooled crystal and 20-25 ma value for the gallium cooled crystal, indicating the presence of thermal distortions. Nonetheless the superiority of liquid gallium cooling expected flux at currents of 60 milliamps and above. This is due in large part to the fact that the crystal and coolant channel geometries were not optimized for the power loadings and coolants used here. For the same power loading, considerable improvement in the peak diffracted intensities should be realized through optimization of crystal and coolant channel dimensions. A program is currently underway at the APS aimed at the optimization of crystal cooling configurations. This will give an indication of whether liquid gallium will be sufficient for the cooling needs of the next generation synchrotron radiation sources or whether more elaborate cooling schemes will be required.

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FIGURE CAPTIONS

Fig.1 Geometry of the crystal used in this study. A Si (111) crystal with three internally drilled coolant channels was used in the experiment. Power incident on the crystal was 7.18 W/ma, corresponding to 430 watts at 60 ma.

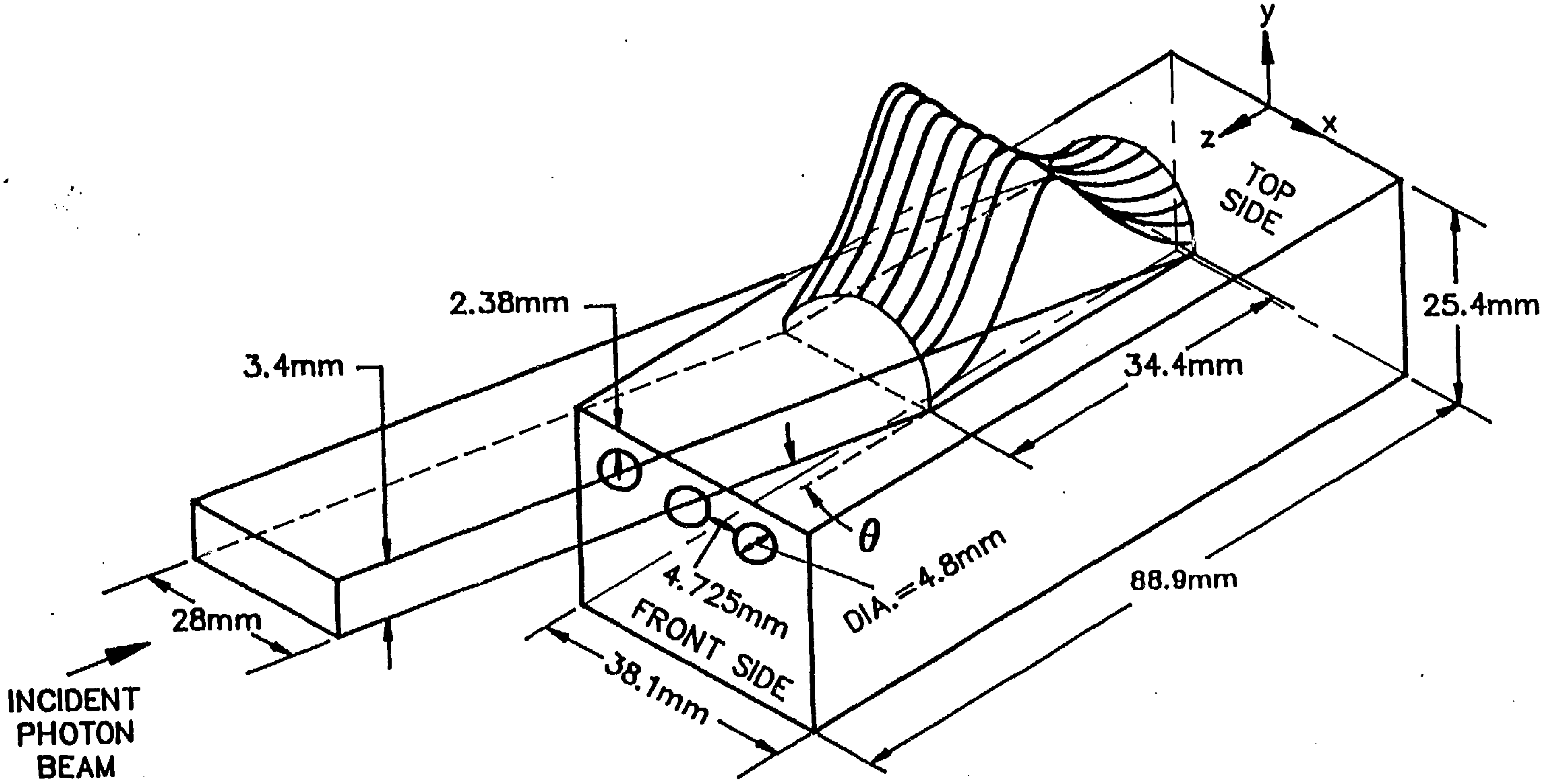
Fig. 2 Meshing scheme used in the finite element modeling. The mirror symmetry around the y-z plane was used to reduce the total number of elements used in the calculation to 5751 and the number of nodes to 7224.

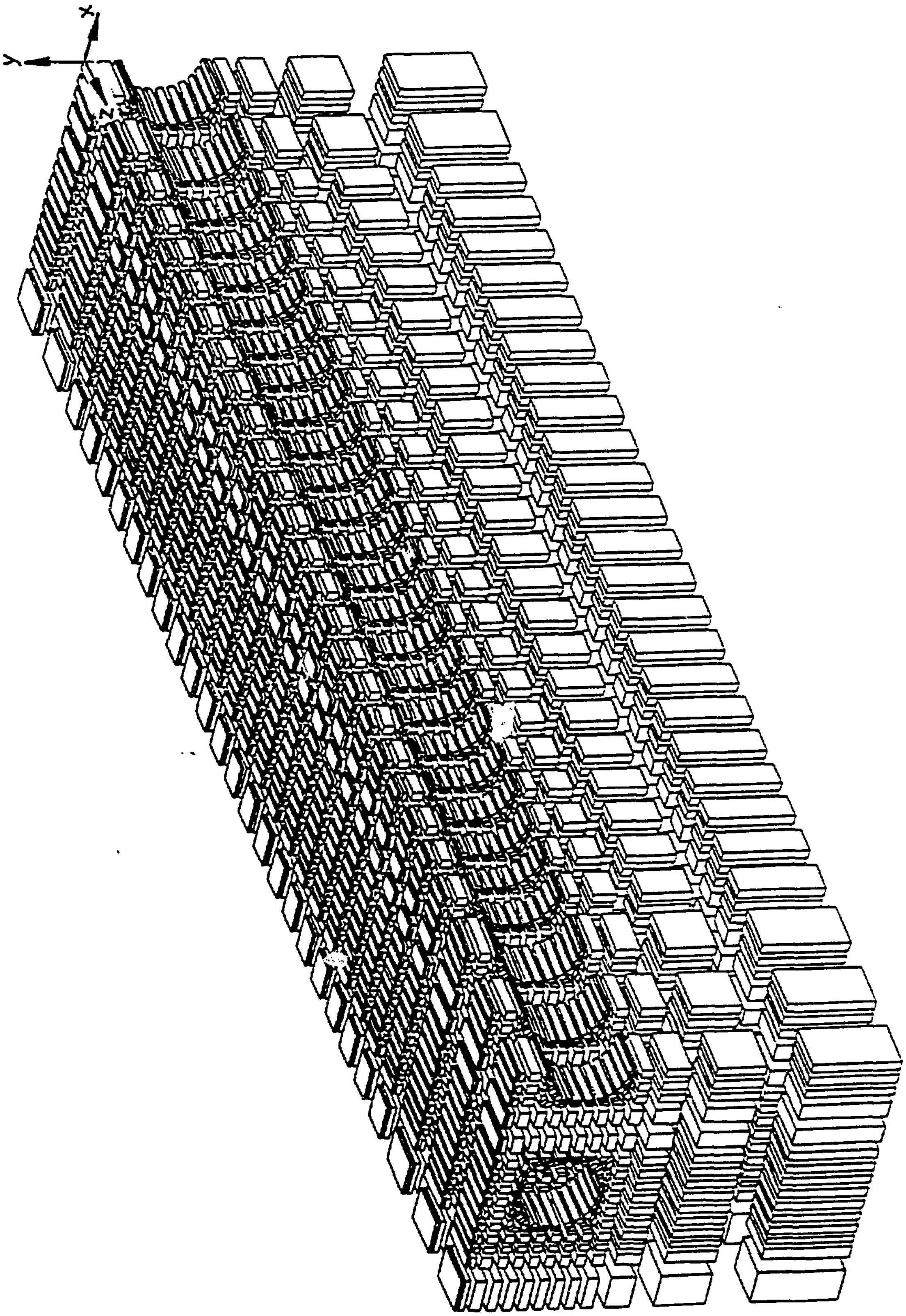
Fig. 3 Calculated thermal profile as a function of distance along the crystal (in the y-z plane) for the liquid gallium and water cooled crystals. The beam footprint is also shown (± FWHM).

Fig. 4 (a) Calculated thermal distortion and corresponding slope error (along x=0) for the liquid gallium cooled crystal. (b) Calculated thermal distortion and corresponding slope error (along x=0) for the water cooled crystal.

Fig. 5 Calculated rocking curves for the gallium cooled and water cooled crystals with the distortions shown in Figs 4a and 4b. Note that there is good agreement in the general shape and width of the calculated and experimentally determined curves.

Fig. 6 Experimentally measured rocking curves with ~60 ma of beam for the Si (111) monochromator set to diffract at 20 keV. The (undistorted) rocking curve full width at half maximum (FWHM) is ~4 arc seconds. The measured FWHM's were 11.7 arc seconds and 21. arc seconds for the liquid gallium and water coolants respectively.


y
z
x
TOP SIDE
25.4mm
2.38mm
3.4mm
34.4mm
θ
DIA.=4.8mm
4.725mm
88.9mm
28mm
FRONT SIDE
38.1mm
INCIDENT PHOTON BEAM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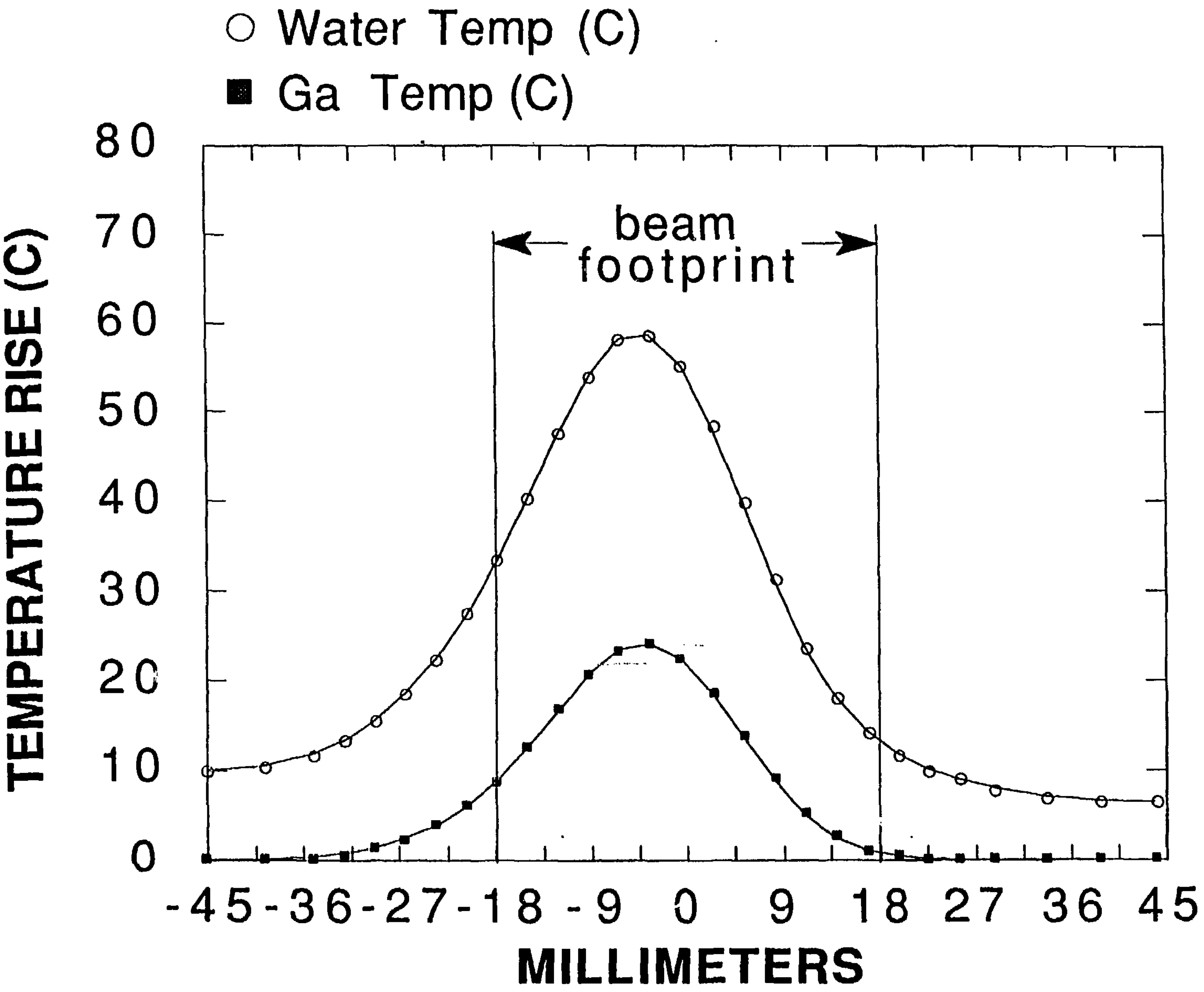
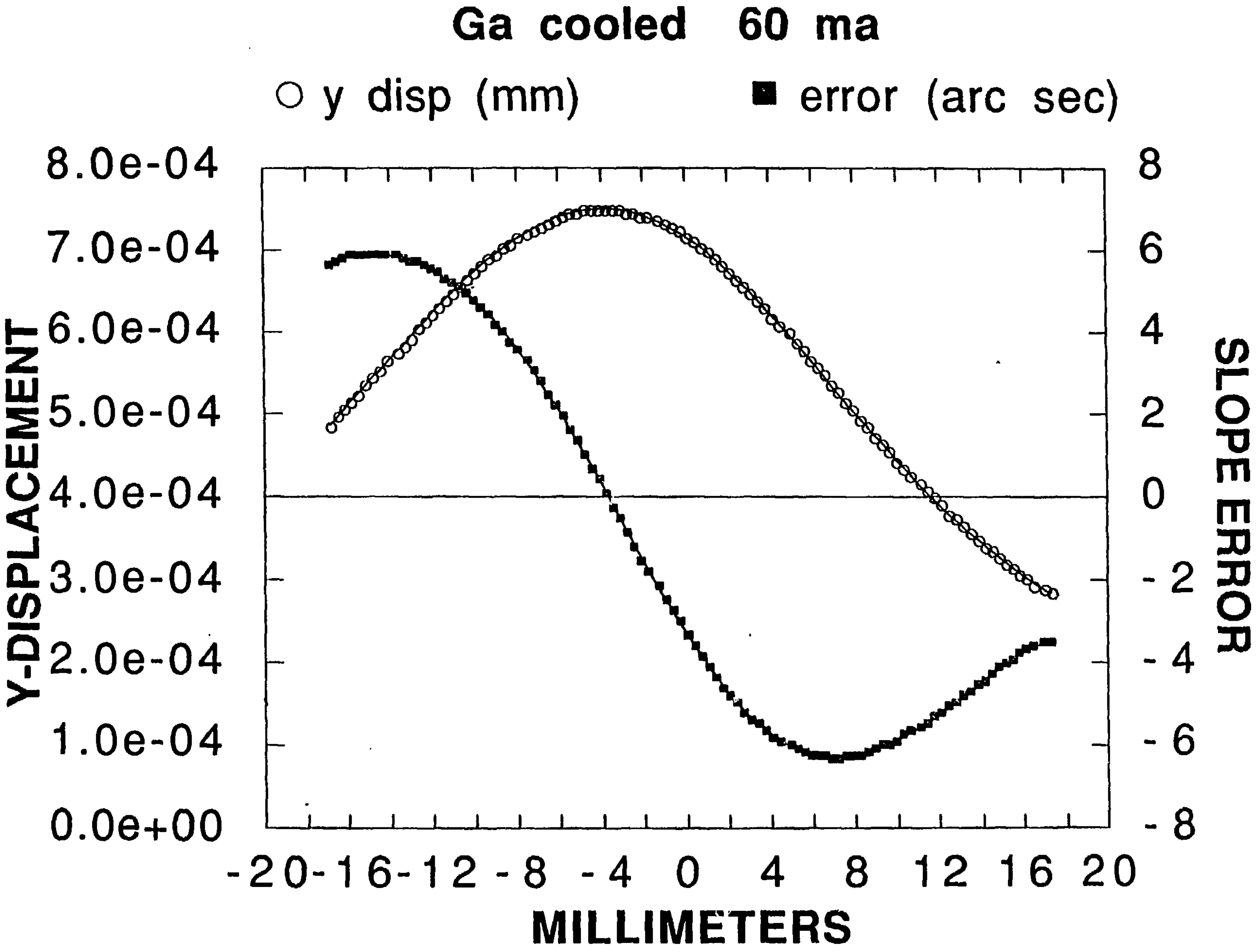

○ Water Temp (C)
■ Ga Temp (C)
TEMPERATURE RISE (C)
0
10
20
30
40
50
60
70
80
beam footprint
-45
-36
-27
-18
-9
0
9
18
27
36
45
MILLIMETERS


Ga cooled 60 ma
○ y disp (mm)
■ error (arc sec)
Y-DISPLACEMENT
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7.0e-04
6.0e-04
5.0e-04
4.0e-04
3.0e-04
2.0e-04
1.0e-04
0.0e+00
SLOPE ERROR
8
6
4
2
0
-2
-4
-6
-8
-20
-16
-12
-8
-4
0
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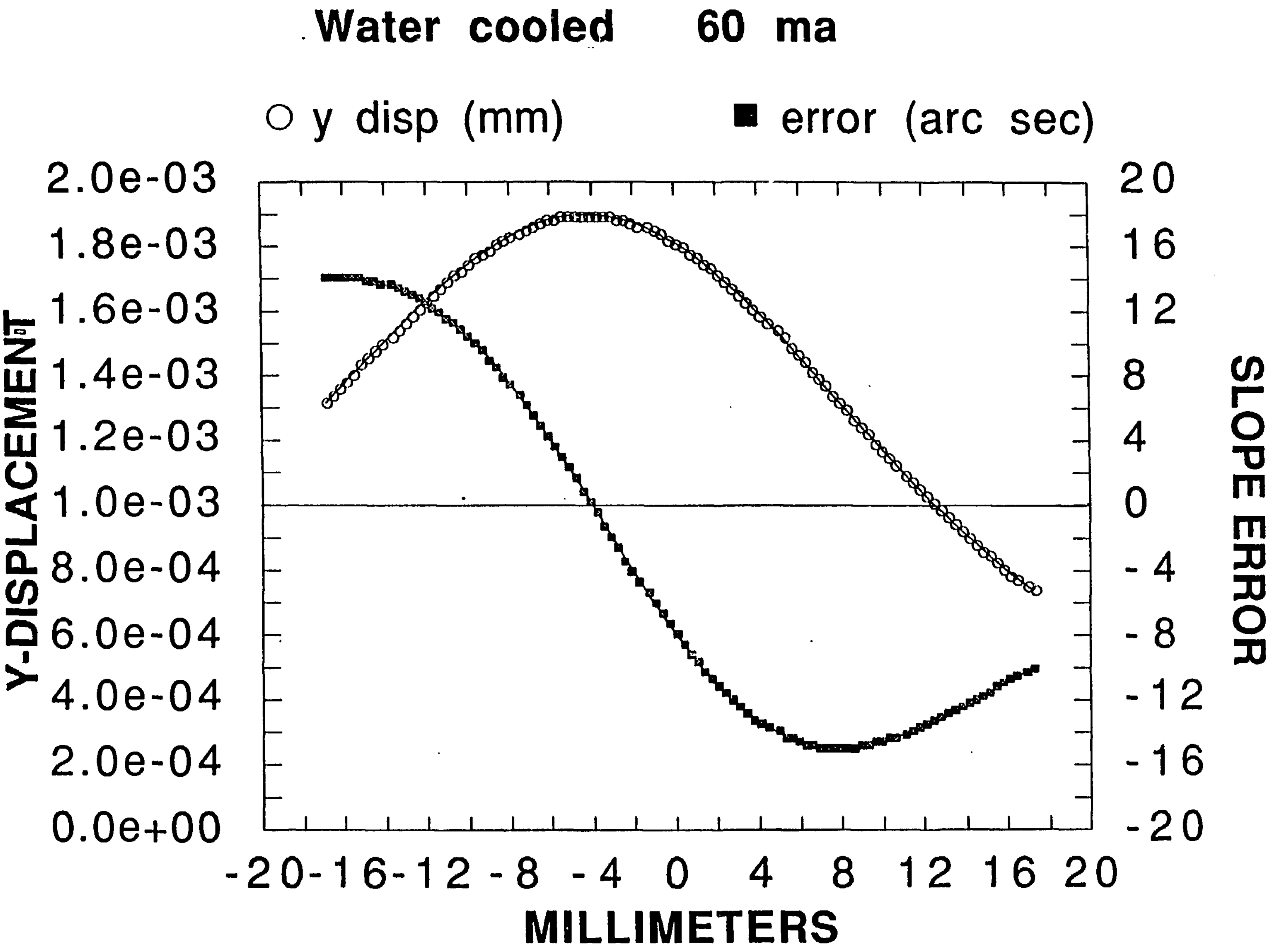
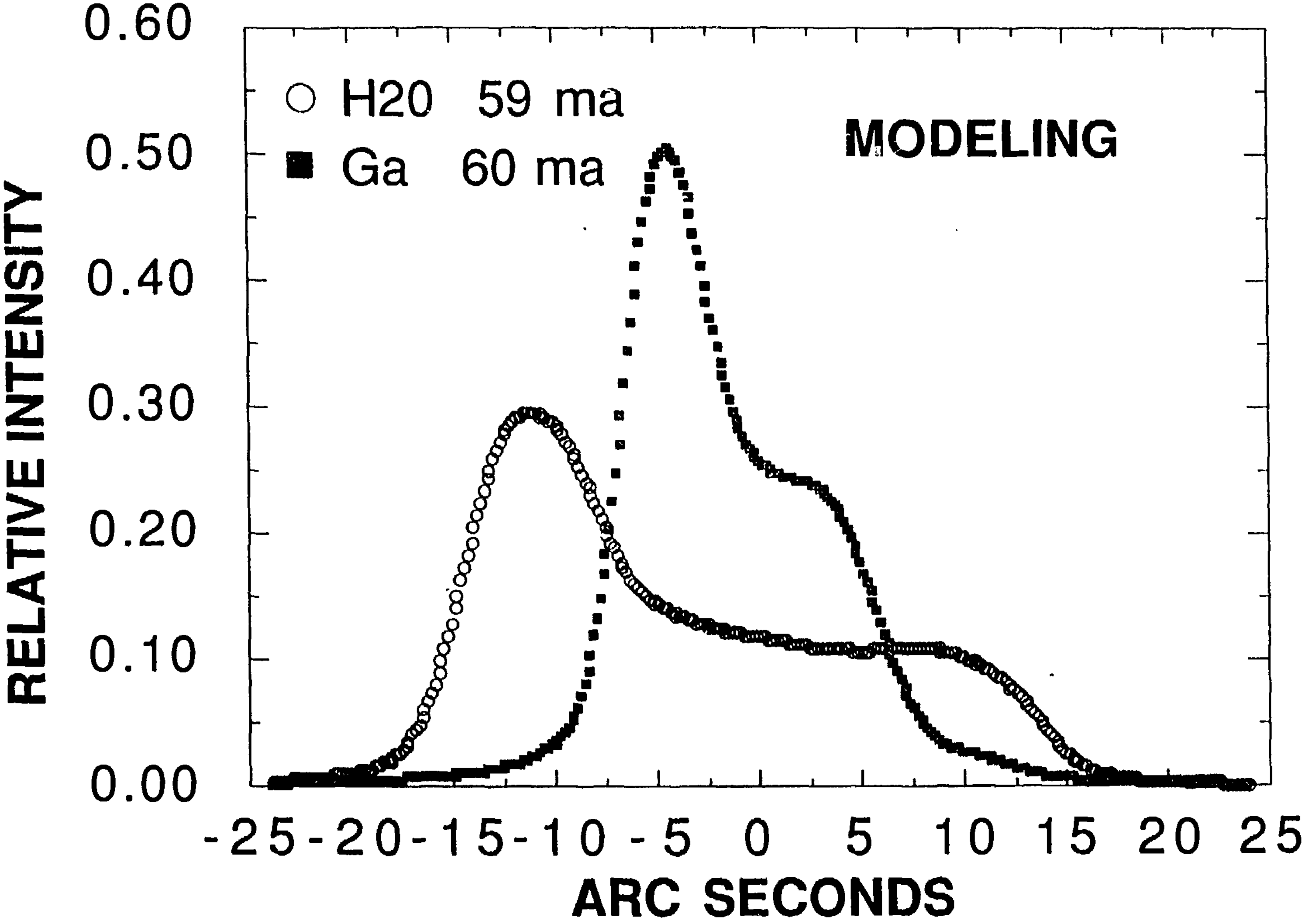
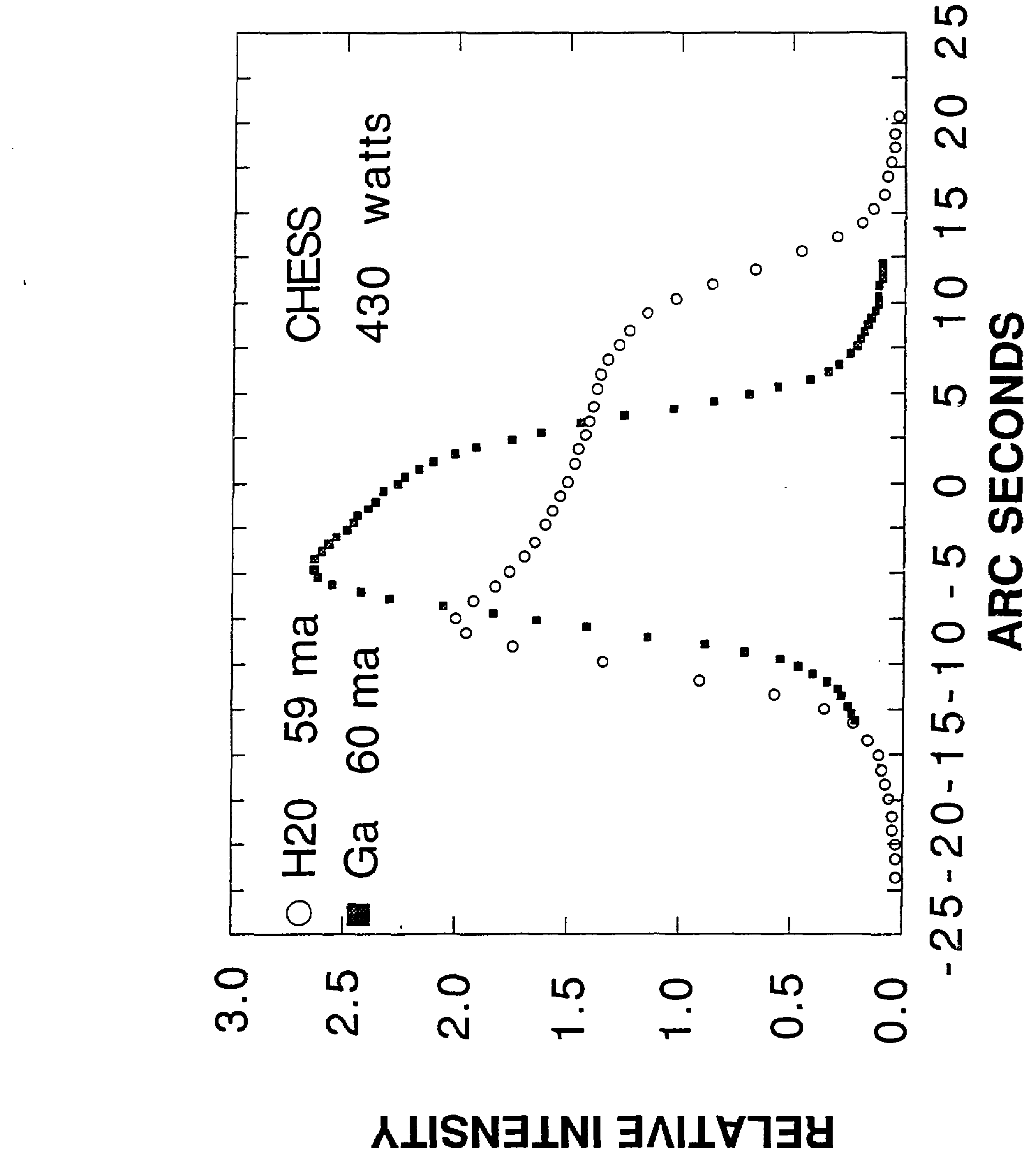
8
12
16
20
MILLIMETERS



Water cooled 60 ma


○ H20 59 ma
■ Ga 60 ma
MODELING
RELATIVE INTENSITY
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-25
-20
-15
-10
-5
0
5
10
15
20
25
ARC SECONDS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■ Ga 60 ma
CHESS
430 watts
-25 -20 -15 -10 -5 0 5 10 15 20 25
ARC SECONDS
0.0 0.5 1.0 1.5 2.0 2.5 3.0
RELATIVE INTENSITY