

# THERMAL ANALYSIS OF HIGH HEAT LOAD MIRRORS FOR THE IN-SITU NANOPROBE BEAMLINE OF THE APS UPGRADE\*

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## Abstract

The Advanced Photon Source (APS) is currently in the process of upgrading to a multi-bend achromat (MBA) storage ring, which will increase brightness and coherent flux by several orders of magnitude. The planned In-Situ Nanoprobe (ISN) beamline, one of the feature beamlines of the APS Upgrade (APS-U) project, is a 220 m long beamline that aims to focus the x-ray beam to a spot size of 20 nm or below by focusing with a KB pair. A double-mirror system, consisting of a high heat load mirror and a pink beam mirror, is designed to provide high harmonic rejection, reduce the power transmitted to the monochromator, and focus the beam along the vertical direction to a beam-defining aperture (BDA). One of the key issues is to manage the high power and power density absorbed by these mirrors. To attain the best focus at the BDA, the pink beam mirror needs to be mechanically bent to correct for thermal deformations on both mirrors. In this paper we report on the thermal responses of the mirror system to different undulator tunings and cooling schemes as calculated with Finite Element Analysis (FEA) and optical ray tracing.

## INTRODUCTION

The ISN beamline will allow high-resolution imaging, spectroscopy, and tomography of energy materials and energy devices, as well as of other complex, hierarchical systems under in-situ and operando conditions. A flat high heat load mirror, M1, is located at 28 m from the source. A bendable pink beam mirror, M2, located 29 m from the source is used to focus the x-rays in the vertical direction from the source to the BDA, which is located at 26 m downstream of M2 (see Fig. 1). Both mirrors deflect the beam by 5 mrad (2.5 mrad grazing angle) in the vertical direction. Ray tracings show a focus at the position of the BDA without visible coma as expected from the near 1:1 focusing.

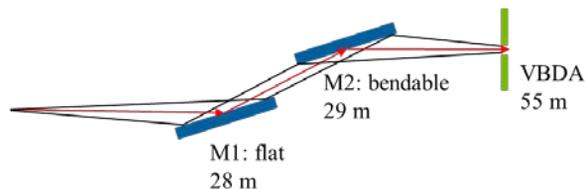


Figure 1: Schematic of the M1 and M2 mirrors of the ISN beamline focusing to the BDA.

M1, which is a flat mirror and deflects the white undulator beam is placed as close to the source as possible, to allow a secondary focus as far upstream as feasible, without reducing the size of the secondary source below the original source size.

To determine the effect of the heat load induced deformations on the spot size at the BDA location, the absorbed power by the mirrors was calculated using SRCalc [1] followed by several FEA calculations. The deformed output of the FEA was subsequently used in the ray tracings with and without the bending required to correct for the thermal deformation of the system.

## THERMAL ANALYSIS

The insertion device designed for the ISN beamline has a 25 mm period and is 4.6 m long. Calculations were performed when the insertion device was tuned to emit photon energies between 5 keV to 12 keV at 1000 eV increments. The power absorbed by each of the mirrors was calculated assuming 200 mA stored in the 6 GeV storage ring. The power densities were imported into ANSYS and applied as a heat flux on the surface of the mirrors. The absorbed power density on the M1 mirror when the undulator is tuned to emit 5 keV is shown in Fig. 2. As seen in the figure, the absorbed power density does not vary significantly in the illuminated area. This is also the case for all energies investigated.

ANSYS Workbench version 18.2 was used in the steady state thermal analysis of the M1 and M2 mirrors. Both M1 and M2 mirrors are 400 mm long, 50 mm wide, and 50 mm thick.

### Simple Side Cooling

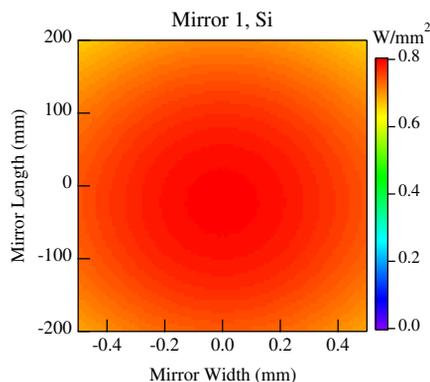


Figure 2: Absorbed power profile on M1 at 5 keV.

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For this analysis we assume side cooling spanning the entire length and height of the mirror. The OHFC copper cooling blocks on both sides of the mirror are 12.7 mm in width with 9.5 mm diameter cooling channels. The cooling channel centers are 12.25 mm from the top of the block. The film coefficient between the water and the cooling channels was calculated to be 5000 W/(m<sup>2</sup>·K). A schematic representation of the mirror and the cooling blocks is shown in Fig. 3.

Thermal contact resistance across the copper-silicon interface with an Indium Foil layer between them is approximately 8000 W/(m<sup>2</sup>·K) [2]. The temperature distribution

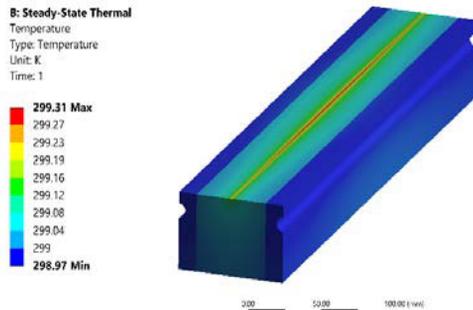


Figure 3: ANSYS model and temperature of M1 Mirror at 5 keV.

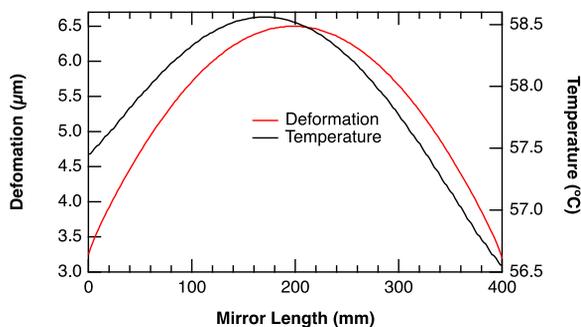


Figure 4: Temperature and deformation of M1 at 5 keV along the central line.

obtained from the FEA when the first mirror is exposed to the power emitted by the insertion device tuned to 5 keV is shown in Fig. 3. The narrow stripe along the mirror center corresponds to the area illuminated by the x-ray beam. The temperature along the mirror length at its center and the deformation normal to the optical surface are shown in Fig. 4.

A smaller, but similar deformation is also seen on M2. The derivative of the convex shape on both mirrors is almost linear indicating a nearly constant radius of curvature in each mirror.

The ray tracings at the position of the BDA with the ideal mirror surfaces (left panel) and those obtained from the FEA calculations (middle panel) are compared in Fig. 5. As seen in the figure, the absorbed power on the mirrors increase the vertical FWHM from 16.5 μm to more than 1 mm due to the defocus. These results allow one to calculate the radius of curvature necessary to correct for the defocus. The right panel in Fig. 5 shows ray tracings at the position of the BDA obtained by bending the M2 mirror to a cylinder with a 4.38 km radius. With the correction the vertical FWHM is nearly the same as the ideal case. Table 1 summarizes the results for four of the eight energies studied. The table lists the power absorbed by each of the mirrors, the vertical spot sizes for the ideal, the uncorrected and the corrected cases that were studied. Finally, the table shows the required radius of curvature at M2 to achieve the corrected case, which provides an almost perfect focus at the BDA.

Table 1: Summary of Results for Selected Energies

Photon Energy (keV)	5	7	9	12
Power absorbed by M1 (W)	429	260	130	20.3
Power absorbed by M2 (W)	10.6	9.06	6.23	5.79
Focal Size at BDA (μm), FWHM Theoretical	16.6	14.4	13.0	11.6
Focal Size at BDA (μm), FWHM Uncorrected	1129	589	257	47
Focal Size at BDA (μm), FWHM Corrected	16.8	14.2	13.0	11.6
Corrected M2 Radius (km)	4.38	5.72	7.51	10.1

Some experiments at the ISN beamline will require scanning photon energy. Therefore, we performed an analysis to determine the change in focal spot size at the BDA using a fixed radius of curvature. The ray tracings were performed with the radius of M2 being 4.38 km, which is optimized for 5 keV. When tuning the undulator energy from 5 keV to 5.1 keV, the beam size obtained at the BDA increased from the “ideal” 16.8 μm to 21 μm. This means the

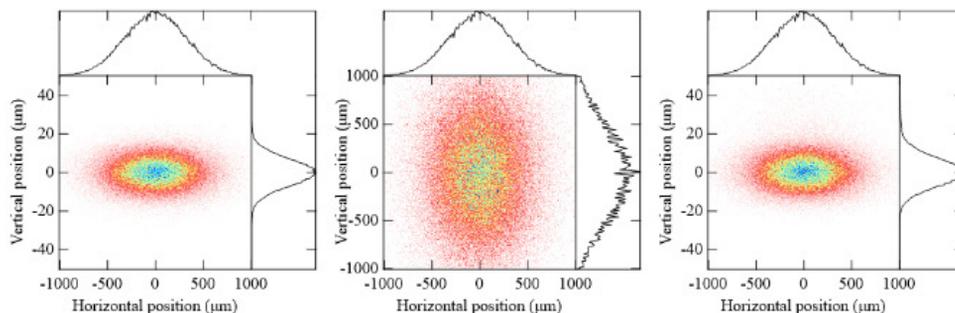


Figure 5: Ray tracing results. Beam profile at the BDA position (left) with ideal mirror surfaces, (middle) with thermal deformation from FEA calculations without M2 bending correction, and (right) with M2 bending correction.

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flux at the sample will vary due to lower transmission through the BDA.

### Notch Design

It has been shown that the mirror deformation can be reduced by an order of magnitude by adding a notch to the mirror side and only applying cooling above the notch. By placing the notch approximately 1/3 of the way down from the optical surface, the notch dimensions can then be optimized to reduce the deformation for certain energies [3, 4].

The notch dimensions on M1 were optimized for the power absorbed at 5 keV. The temperature profile of the M1 mirror with the optimized notch are shown in Fig. 6.

Figure 7 compares the vertical deformation obtained with the simple side cooling to the optimized notch. As seen on the figure the deformation is indeed reduced by more than an order of magnitude and produced a near flat shape especially in the central portion of the mirror (slope error within the central 300 mm is 0.14  $\mu$ rad). The small increase in focal spot size could greatly reduce the amount of bending needed by the M2 mirror.

For comparison with previous energy scan results, powers at 5 keV and 5.1 keV energies were applied to this design, and then compared with the energy scan for the regular no notch design. The M2 radius was held constant at 4.38 km as before. The notched design showed a change in focal size from 17.2  $\mu$ m to 17.0  $\mu$ m going from 5.0 keV to 5.1 keV respectively. This is a significant reduction in change of focal spot size. In addition, the focal position change relative to the BDA decreased from -1.7 m to 0.1 m going from the normal side cooled design to the notch design respectively.

### Internally Cooled

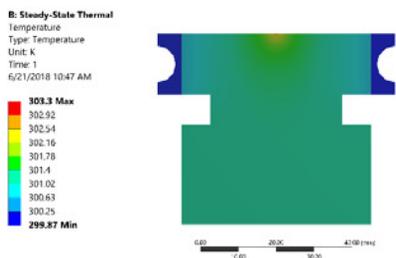


Figure 6: Temperature profile of M1 for the notch design at 5 keV.

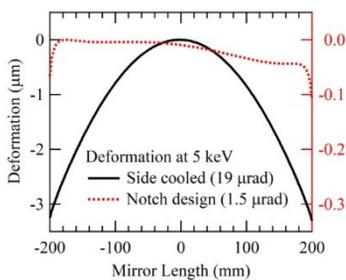


Figure 7: Thermal deformation of M1 comparison of side cooled and notch design at 5 keV.

Internally cooled mirrors have been studied previously in hopes of finding a significant reduction in thermal distortions on high heat load optics [5]. Such mirrors have also been considered as an option for the M1 and M2 mirrors of the ISN beamline. The results of the internal cooling studies show an order of magnitude less thermal deformation than a normal side cooled mirror, but not enough to completely remove the thermal bump without further correction. The surface deformation is more complicated due to the cooling channel design and coolant pressure, thus a simple bending correction may not be adequate. Since the accurate modeling of internally cooled mirrors is difficult, further studies are still needed.

## CONCLUSIONS

The combined FEA and ray tracings show that the mirror system composed of a flat mirror and a bendable mirror that are side cooled will practically maintain the vertical spot size at the aperture. Scanning undulator energy without actively bending the M2 mirror will increase the spot size at the BDA when the insertion device changes power. Preliminary results show promise for the notch design in greatly reducing the beam spot size due to thermal deformation. Furthermore, the design allows scanning with a fixed radius of curvature without a significant increase in spot size. For the APS upgrade project, we are actively looking into different cooling schemes, coolants and designs.

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