THERMOMECHANICAL DESIGN OF NORMAL-CONDUCTING DEFLECTING CAVITIES AT THE ADVANCED PHOTON SOURCE FOR SHORT X-RAY PULSE GENERATION*

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Abstract

A normal-conducting deflecting cavity is being designed at the Advanced Photon Source (APS) as a part of the short x-ray pulse project intended to provide users with approximately 2 picosecond x-rays. The system will use two pairs of 3-cell cavities in sectors 6ID and 7ID for the generation of the x-ray pulse in the 7ID beamline. The 3-cell cavities are designed to provide the desired beam deflection while absorbing in excess of 4 kW of power from a pulsed rf system and up to 2.6 kW in the damper system of high-order mode (HOM) and low-order mode (LOM) waveguides. Since the cavity frequency is very sensitive to thermal expansion, the cooling water system is designed so that it is able to control cavity temperature to within 0.1°C. This paper describes the optimization of the thermomechanical design of the cavity based on calculation of thermal stresses and displacement caused by the generated heat loads, and presents the design of a cooling water system required for the proper operation of the cavities.

INTRODUCTION

Research using time-resolved x-ray techniques is well established at the APS, and researchers using these techniques have contributed greatly to the understanding of structural changes on the ≥ 100 ps time scale. In order to ensure that the APS remains a leader in time-resolved x-ray techniques, a short-pulse x-ray (SPX) system will be built that is capable of producing ≈ 2 ps x-ray pulses, while preserving a substantial portion of usable flux. This project will offer a unique bridge for hard x-ray science between capabilities at current storage rings and future x-ray free-electron lasers [1].

Normal-conducting, 3-cell deflecting cavities and a standard undulator will be used to generate short-pulse x-rays. The layout being considered for the picosecond timing system is shown in Figure 1 and will utilize both 6ID and 7ID straight sections of the APS storage ring. Two 3-cell cavities will be installed on the downstream end of each undulator. The first pair of cavities will tilt the bunch before it enters the undulator at 7ID and the second pair will tilt it back to its normal orbit, thus ensuring standard operating conditions for all other sectors at the APS [2].

THERMAL DESIGN

There are two sources of heat generation that have been considered in the thermal design of normal-conducting deflecting cavities at the APS. The first source is a heating due to the operating mode at 2815 MHz. This is the primary mode of heat generation in the cavity proper and is calculated to be 4.1 kW. The second source of thermal load is the power loss due to HOM/LOMs that have been extracted from the cavity as propagating waveguide modes. This source of power loss is predominant in the damper system of the cavities. Total power loss in the damper system due to inadvertent coupling with the operating mode and due to the extraction of the parasitic modes is 2.6 kW, for the worst case operational fill pattern at the APS where a maximum beam current of 130 mA has been assumed.

We are presenting a thermal design of the cavity that is capable of absorbing the power losses while both maintaining thermally induced stresses in the cavity below the yield stress values of OFE copper and limiting the deformation of the cavity such that the frequency shift caused by this deformation stays within acceptable limits.

Thermal Optimization of the Cavity

The operating mode of the deflecting cavities is a dipole mode and, due to the field distribution of this mode, most of the heat is generated in a limited region on the iris of the cavity, close to the plane where the magnetic fields of the dipole operating mode meet (Figure 2). This region of the cavity is not easily accessible to cooling; therefore the cooling has to be carefully designed. Initial computations of thermal stresses for the original shape of the irises were very high and it became necessary to optimize the shape of the iris. The first step

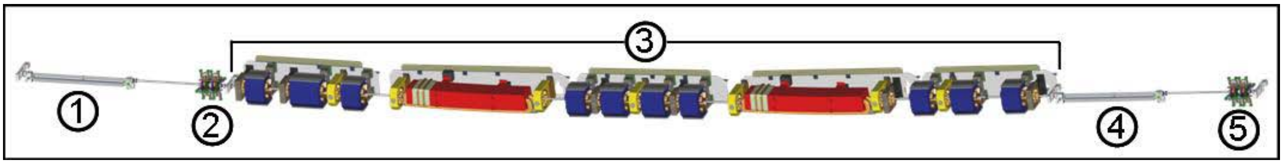

Figure 1: Layout of Short X-Ray Pulse System at the APS. 1-Sector 6ID Undulator vacuum chamber; 2-the first pair of the cavities; 3-sector 7ID girders; 4-sector 7ID undulator vacuum chamber; 5-the second pair of the cavities.

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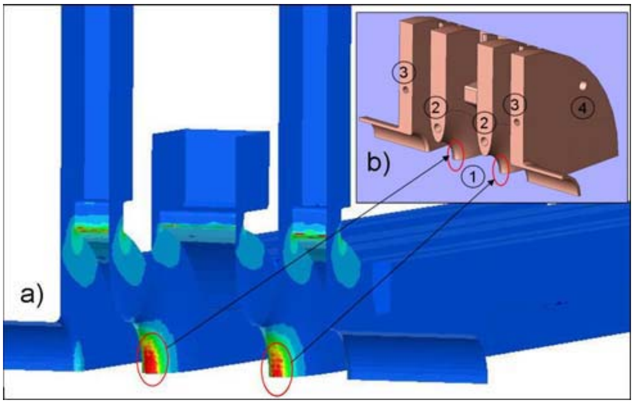

Figure 2: Power deposition at the surfaces of normal-conducting deflecting cavity at APS. a) HFSS computations, b) solid model of the cavity proper (no waveguides). 1-Regions of peak power generation; 2-cooling channels in coupler cell irises; 3- cooling channels in end cell irises; 4-peripheral cooling (optional).

was to establish the maximum acceptable stress level in the cavity structure. Research at Argonne National Laboratory indicates that, with the controlled temperature regime of brazing furnaces, the value of the yield stresses of the copper after brazing can be consistently kept at 80 MPa [3]. Based on this research, a value of 50 MPa was adopted as a maximum allowed stress value in the cavities. The next step was to determine the optimal size of the iris. The minimum diameter of the iris opening was determined by the ray-tracing requirements to be 44 mm. Further increase in the diameter of the iris opening leads to a reduction in cavity shunt impedance, an increase of peak power, and, consequently, higher levels of thermal stresses. Therefore, a 44 mm iris diameter was adopted. Initial designs using 4 to 6-mm-thick iris were abandoned when it became apparent that no acceptable

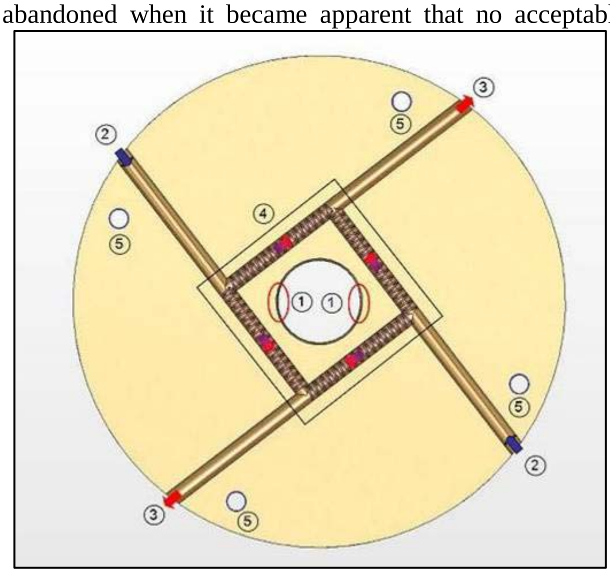

Figure 3: Schematics of the cavity cooling. 1-Regions of peak power generation; 2-water inlets; 3-water outlets; 4-the region of intensified convective cooling; 5-peripheral cooling (optional).

scheme for cooling such a thin iris was available. The thickness of the iris was increased and the cooling system shown in Figure 3, similar to the cooling system reported in [4], was adopted. In order to increase the cooling efficiency in the region of peak power losses, a set of coils will be placed into the cooling channels to increase the convective heat transfer coefficient [5]. Temperature fields and thermal stresses were computed for 12- to 20-mm-thick irises. HFSS software was used to calculate power loss of 4.1 kW. Computed power loss distribution was then transferred to the Cosmos software package, which was used for the computation of the temperature and thermal stress distribution. The analysis was performed on a single-cell 3D model that represented a 'typical' cell. The results show that the stresses in the 15-

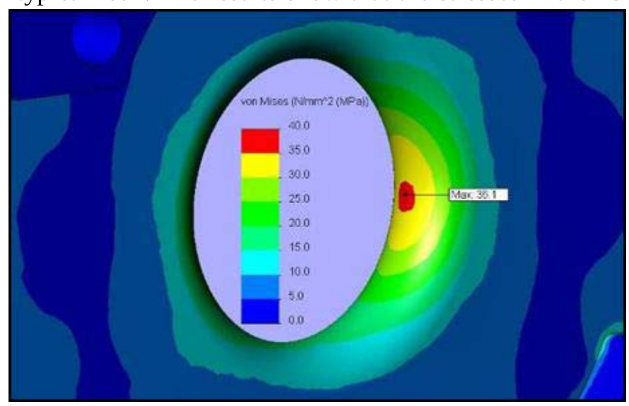

Figure 4: Thermal stresses calculated for 15-mm-thick iris of a 'typical' cell.

mm-wide iris with a cylindrically shaped tip remain below 50 MPa (Figure 4). For the elliptically shaped tip of the iris, needed to ensure proper cell-to-cell coupling, the thickness was increased to 18 mm in order to keep the maximum stress below 50 MPa.

A comprehensive coupled field analysis of the rf-generated field, thermally induced deformation, and frequency shift using ANSYS Multiphysics is in its final stage, and the results will be published separately. Obtained results indicate that the proposed cavity design will perform within the requested limits.

Thermal Design of the Damper System

The thermal design of the damper system has to ensure that the damper structures survive brazing of silicon carbide (SiC) dampers to the OFE copper substrate and that the heat generated during the operation is efficiently removed by cooling of the substrate. To reduce thermal stresses developed after brazing, the SiC layer is split into individual tiles separated by 1-mm gaps. The tiles have a 40×40 mm base, and their thickness gradually drops from 7 to 1 mm. The surface of copper substrate is machined to form a matrix of needle-like posts, and the SiC tiles are brazed atop the pins, similar to the design given in [6]. Pin posts have a 2.5×2.5 mm cross section and are 3 mm long. Each set of tiles creates a 40×300 mm damper structure. There are two damper structures per damper waveguide (Figure 5).

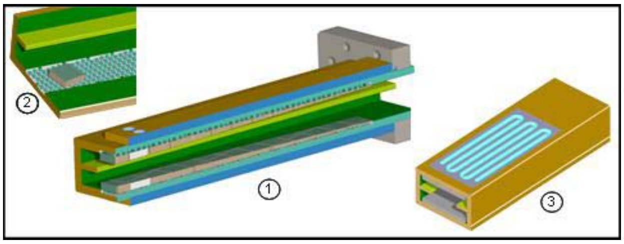

Figure 5: Damper structure. 1-Section view of the structure; 2-individual SiC tile brazed atop the copper pin matrix; 3-cooling channels incorporated in copper walls.

The 'tiling' of the damper structure greatly reduces the length of the contact between SiC and copper. In addition, flexible pins conform to the displacement caused by the difference in the thermal expansion coefficients of SiC and copper and effectively decouple tiles from the substrate. The pin matrix reduces the efficiency of the cooling of tiles due to the decrease in the contact surface with the cooled substrate, yet the computed temperature distribution indicates that the cooling of the damper structure is adequate and that the temperature difference in the damper structure remains below 10°C (Figure 6).

Cooling System

The rf cavities of the short pulse x-ray system require precise temperature control in order to tune and maintain the cavity frequency over the required range of operation. To meet the operating requirements, the cooling system must achieve better than 0.1°C temperature stability, and the system must automatically adjust the cooling water supply temperature to keep each cavity at near constant temperature across the operating range.

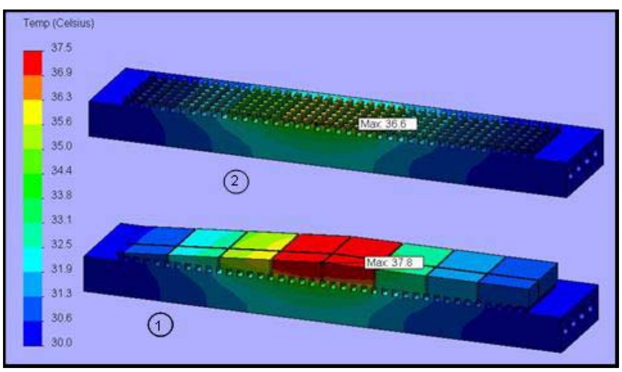

Figure 6: Temperature distribution in the dampers. 1-Entire structure; 2-copper substrate.

The rf cavities will be tuned at room temperature with an offset such that the cavities must be elevated above room temperature in order to match the cavity resonant frequency with the klystron driving frequency. Thus, the cooling water system must always operate above the ambient air temperature inside the storage ring. To achieve precise temperature control and stability, two separate stages of heat exchange are required for each cavity. The first stage of heat exchange is expected to bring the flow streams to within 1.0°C or better of the target temperature. The second-stage heat exchangers are much smaller than the first-stage heat exchangers and are located close to the cavities. They will deliver the tempered cooling water with better than 0.1°C stability across the operating range. The temperature range for the cooling system is adjustable from 30°C to 50°C.

MECHANICAL DESIGN

The cavity structure will be built from individual cells, machined from OFE copper and joined by hydrogen furnace brazing. HOM/LOM waveguides, also brazed in place, will be manufactured from OFE copper with metal seal vacuum flanges welded at the ends to facilitate modular type SiC dampers. SiC dampers will be installed as add-on modules mounted onto the waveguides. First the SiC damper tiles will be brazed to the OFE copper substrate halves, and then the halves will be e-beam welded together and to the metal seal flanges.

CONCLUSIONS

A design for a novel normal-conducting deflecting rf cavity that is used to generate short-pulse x-rays on the picosecond timescale is being developed at the APS. Efficient cooling ensures that the thermal stresses in the structure remain below the yield stress value. The proposed design of the damper structure is based on known brazing concepts and will be efficiently cooled. A two-stage cooling system will provide the required 0.1°C temperature stability within the 30-50°C temperature operating range of the cavities.

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REFERENCES

[1] Time-Domain Workshop: Summary and Recommendations, September 2004 http://www.dev.aps.anl.gov/News/Conferences/2006/APS Upgrade/Time-domain_summary.pdf.
[2] A. Zholents et al., NIM A 425, 385 (1999).
[3] W. Toter, private communication, wtoter@anl.gov.
[4] V.V. Paramonov et al., "Design Parameters of the Normal Conducting Booster Cavity for the Pitz-2 Test Stand," LINAC'04, Lübeck, August 2004, p. 204, http://www.jacow.org.
[5] J.T. Collins et al., "Enhanced Heat Transfer Using Wire-Coil Inserts for High-Heat-Load Applications," MEDSI 2002, Argonne, September 2002, p. 409, ANL-03/7.
[6] G. G. Cheng et al., "RF-Thermal-Structural Analysis of a Waveguide Higher Order Mode Absorber," these proceedings.

