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DISCRETE PHOTON ABSORBERS FOR THE APS-UPGRADE STORAGE RING VACUUM SYSTEM*

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Abstract

The Advanced Photon Source Upgrade storage ring arc vacuum system features a diverse set of photon beam-intercepting components, including five discrete photon absorbers and a series of small-aperture vacuum chambers that shadow downstream components. The discrete photon absorbers—typically fabricated from electron beam-welded GlidCop® AL-15—are subject to heat loads ranging from approximately 170 to 3400 watts, with a peak power density up to approximately 610 W/mm^2 at normal incidence. Four of the five photon absorber designs are housed in vacuum chambers, including three that are mounted to the antechambers of curved aluminum extrusion-based L-bend vacuum chambers and one that is mounted to a stainless steel vacuum-pumping cross. Furthermore, two of the photon absorbers that are mounted to L-bend vacuum chambers are equipped with position-adjustment mechanisms, which are necessitated by the challenging design and fabrication of the curved vacuum chambers. The fifth photon absorber, unlike the rest, is a brazed design that is integral in sealing the vacuum system and intercepts approximately 170 watts. Each photon absorber design was optimized with thermal-structural finite element analyses while ensuring functional and spatial requirements were met. Some of these requirements include meeting internal high-heat-load component design criteria, respecting challenging component interfaces and alignment requirements, and minimizing impedance effects. Furthermore, photon beam scattering effects called for the use of scattering shields on three designs to minimize potential heating of vacuum chambers. This paper details the careful balance of functionality and manufacturability, and the overall design process followed to achieve the final designs.

INTRODUCTION

The Advanced Photon Source Upgrade (APS-U) project is building a storage ring upgrade that will be retrofitted to the current 1.1-km circumference APS storage ring. By utilizing narrow aperture magnets and thus a small-aperture vacuum system in a multi-bend achromat (MBA) lattice, the upgrade will produce a 6-GeV, 200-mA beam that is optimized for brightness above 4 keV [1].

Five GlidCop® AL-15 discrete photon absorbers (in addition to water-cooled, small-aperture vacuum chambers) were designed to shadow, or protect, neighboring electron and photon beam vacuum components in the APS-U MBA lattice. The final photon absorber designs were driven by several requirements, most notably including: protecting neighboring components in the storage ring vacuum system while safely handling the heat loads produced by the MBA lattice; achieving minimum vertical and horizontal apertures for the photon beams produced by the upstream straight sections and bending magnets; and finally, a need for seamless integration into the storage ring vacuum system.

Three of the five photon absorbers—A:CA1, A:CA2, and B:CA1—are considered “crotch” absorbers and thus permit photon extraction to the front ends while typically intercepting higher heat loads (Fig. 1a-1c). The final two photon absorbers include an “end” absorber, B:EA1 (Fig. 1d), and an “inline” absorber, B:FA1 (Fig. 1e), both of which strictly shadow uncooled downstream components from synchrotron radiation. The B:FA1 inline photon absorber, which is 60 mm in length, serves a dual purpose in that it is a vacuum chamber and also shadows downstream components. Each of the five photon absorber designs are required in the 40 repeating sector arcs of the APS-U storage ring vacuum system.

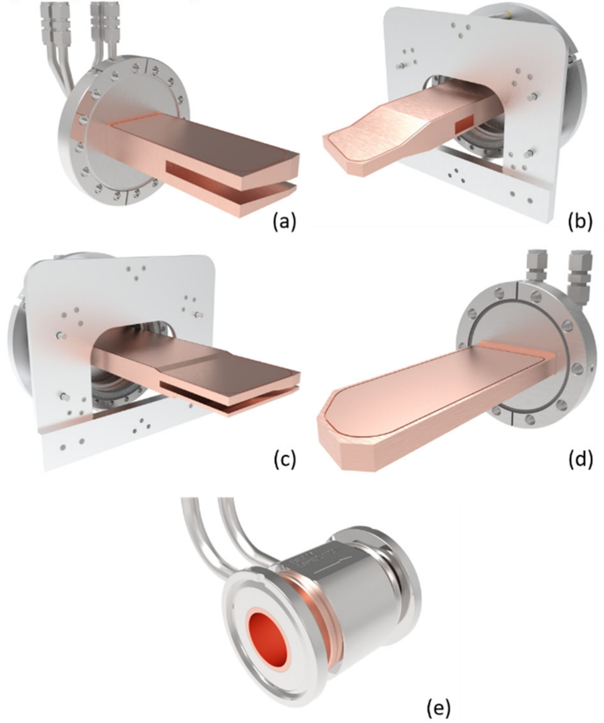

Figure 1: Discrete photon absorber designs, including crotch absorbers (a) A:CA1, (b) A:CA2, and (c) B:CA1, an end absorber (d) B:EA1, and an inline absorber (e) B:FA1.

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INTERFACES

Each photon absorber design required a careful study of interfacing components to ensure a seamless integration into the storage ring vacuum system. The most prominent interfaces include the housing vacuum chamber, downstream vacuum components that must be shadowed, and a need to minimize impedance effects. Secondary interfaces include the water system, survey and alignment needs, and in some cases additional storage ring or front end equipment located outside of vacuum, which further constrained the designs.

Four of the five photon absorber designs are housed in vacuum chambers which, due to the tight confines of the overall storage ring vacuum system, typically meant strict spatial limitations. The A:CA2, B:CA1, and B:EA1 photon absorbers are mounted to the antechambers of stretch-formed aluminum L-bend vacuum chambers, while the A:CA1 photon absorber is mounted to a stainless steel vacuum-pumping cross as shown in Fig. 2.

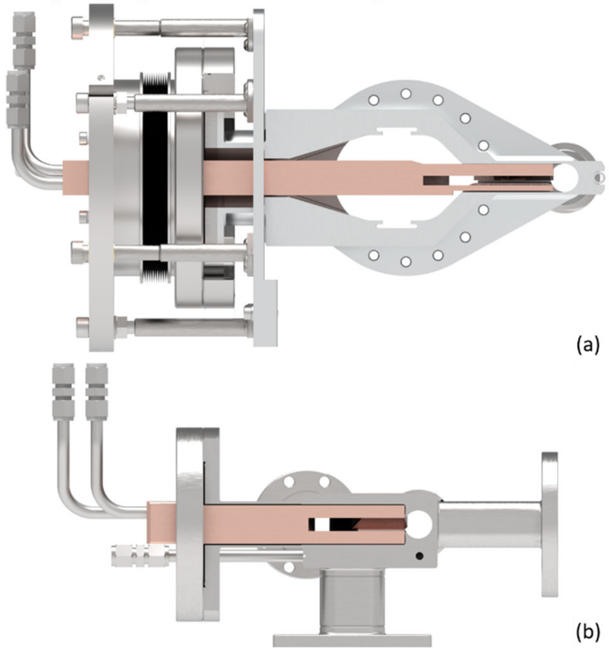

Figure 2: Cross-sectional view of (a) B:CA1 mounted to the B:M2 L-bend vacuum chamber and (b) A:CA1 mounted to the A:VC6 stainless steel vacuum cross.

The interface with the L-bend vacuum chambers was particularly challenging due to their narrow electron beam apertures and pumping slots, which typically limited water-cooling channel geometry to unique, non-circular shapes. Furthermore, nominal gaps of 1 mm to 1.25 mm were designed between the vacuum chambers (including the vacuum cross) and photon absorber surfaces, particularly in the regions closest to the electron beam. These gaps, in addition to beam-intercepting geometry of the photon absorbers, were negotiated with the accelerator physics group to minimize resulting impedance effects while ensuring adequate space for installation and alignment needs.

A skeleton-based CAD model was employed to design all custom vacuum components, which also permitted the creation of an integrated ray-trace model [2]. The ray-trace model, built off the MBA lattice, allowed for subtle adjustments to vacuum component geometry and refinement of designs. Figure 3 portrays the B:CA1 crotch photon absorber mounted to its L-bend vacuum chamber and the components immediately downstream that it must shadow.

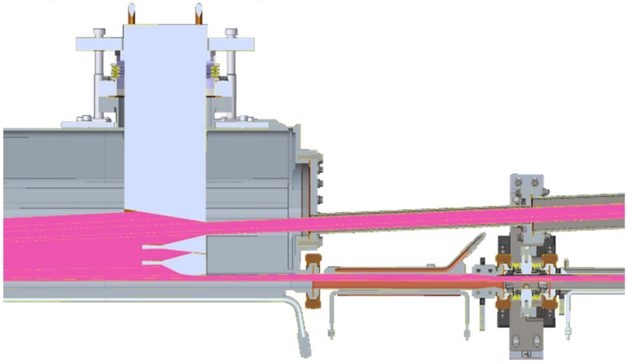

Figure 3: Example ray-trace driven by the skeleton CAD model, with the B:CA1 crotch photon absorber shown.

Using the 3D ray-trace model, beam footprints and corresponding heat loads were calculated for all beam-intercepting components; this data was then utilized as inputs for thermal-structural finite element analyses. From upstream to downstream in the sector arc, Table 1 lists the peak power density at normal incidence and total power for each of the five discrete photon absorbers. A maximum normal power density of 607 W/mm^2 occurs on the B:FA1 inline photon absorber and maximum total power of 3403 W occurs on the B:CA1 photon absorber.

Table 1: Discrete Photon Absorber Heat Loads

Photon Absorber	Normal Power Density (W/mm^2)	Total Power (W)
A:CA1	111	1064
A:CA2	226	581
B:CA1	251	3403
B:EA1	208	559
B:FA1	607	171

DESIGN AND FABRICATION

With the exception of B:FA1, and to maximize the heat removal capacity given the aforementioned strict interfaces, the photon absorbers were each originally conceived as a monoblock copper chromium zirconium (CuCrZr) design that relied primarily on sinker electrical discharge machining (EDM) to machine a "pocket" and electron-beam (e-beam) welding to weld a pocket "insert," which together formed the water-cooling channel and avoided any water-to-vacuum joints, as depicted in Fig. 4a [2]. After consulting with reputable vendors, it was determined that this design would prove to be cost prohibitive and incur significant challenges during the manufacturing process, pushing the limits of today's manufacturing capabilities. Consequently, the final discrete photon absorber designs kept the outer geometry of the CuCrZr variants, but primarily feature e-beam welded GlidCop instead. The primary joining operation of the final designs was intended to be via brazing, however, the contracted vendor proposed e-beam welding in its place.

The change from the CuCrZr to GlidCop designs, in conjunction with strict spatial limitations, posed a new challenge in designing adequate water-cooling while avoiding water-to-vacuum joints. Fortunately (and historically implemented at the APS), adding another layer of material typically negates the concern with such a joint. Figure 4b depicts a cross-sectional schematic of the final design, wherein any potential breach in the water joint can be evacuated to the open air while preserving the vacuum joint.

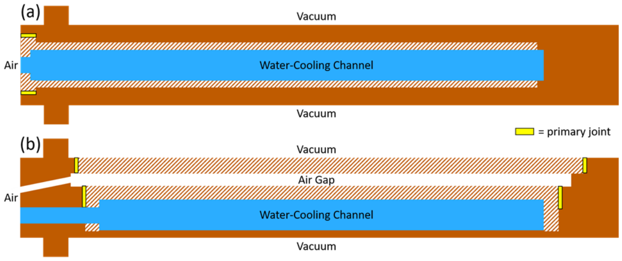

Figure 4: Illustration of a typical discrete photon absorber cross-section for (a) the CuCrZr design and (b) the final GlidCop design.

The production of the discrete photon absorbers will involve several planned manufacturing and incremental quality assurance (QA) steps, with B:CA1 being the most complex. Referring to Fig. 5, machining of the GlidCop B:CA1 photon absorber body—with the exception of the beam-defining edges—and other components such as the copper cover plates and flange components occurs first. The water and vacuum cover plates are then e-beam welded to the GlidCop body, followed by e-beam welding a pre-brazed cooling block and flange adapter disc to the body. The beam-defining edges are then machined via conventional machining and EDM after all e-beam welding to the photon absorber is completed. The bellows-flange assembly is then TIG welded to the photon absorber, followed by assembly of the position adjustment mechanism and water fittings. The B:FA1 photon absorber is a more straightforward brazed GlidCop assembly whose final design was based on that of the integrated photon absorbers that are common to most APS-U non-evaporable getter (NEG)-coated copper vacuum chambers [3]. All photon absorbers will undergo standard vacuum component QA processing, including dimensional evaluation, cleaning, bake-out, vacuum and hydrostatic leak testing, and a final residual gas analysis scan.

Two additional features required by some of the designs include the position-adjustment mechanisms and scattering shields. The A:CA2 and B:CA1 photon absorbers are equipped with position-adjustment mechanisms due to the challenging fabrication of the L-bend vacuum chambers. These mechanisms consist of bellows and supplemental hardware that permit the precise alignment required by the ray-trace. The remaining photon absorbers do not require this adjustable design due to the precise machining of the vacuum cross in the case of A:CA1, or more conservative shadowing incorporated into the nominal B:EA1 and B:FA1 designs. The three crotch photon absorber designs also feature scattering shields, similar to those employed at the European Synchrotron Radiation Facility, whose sole purpose is to recapture power that is potentially scattered from the beam-intercepting surfaces [4]. Though the housing vacuum chambers are equipped with water cooling, the presence of a scattering shield further reduces any potential for overheating these components, particularly for the stainless steel vacuum-pumping cross due to its poor thermal conductivity.

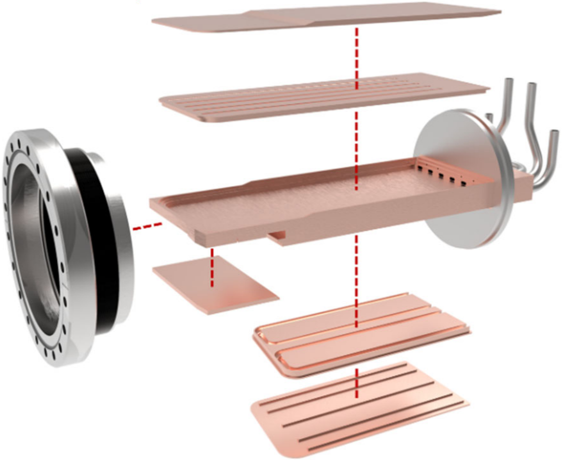

Figure 5: Simplified exploded view of B:CA1, with the major fabrication steps represented.

CONCLUSION

Following an intensive and well-scrutinized design process, the procurement of the discrete photon absorbers is underway with first articles expected in late 2021. Next steps include continued fabrication followed by testing and quality assurance steps, assembly onto the respective magnet modules, and finally, installation into the storage ring tunnel during the APS dark period.

ACKNOWLEDGEMENTS

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