ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-TUPLS11

NEG-COATED COPPER VACUUM CHAMBERS FOR THE APS-UPGRADE STORAGE RING VACUUM SYSTEM*

O. K. Mulvany†, B. Billett, B. Brajuskovic, J. A. Carter, A. McElderry, K. J. Wakefield,
Advanced Photon Source, Argonne National Laboratory, Lemont, IL, USA

Abstract

The APS-Upgrade (APS-U) storage ring features a diverse group of vacuum chambers including seven distinctive, non-evaporable getter (NEG)-coated copper vacuum chambers per each of the 40 sectors. These chambers feature a 22-millimeter diameter aperture along the electron-beam path, with two vacuum chambers permitting photon extraction through a keyhole-shaped extension to this aperture. The chambers range from 0.3-meters to 1.7-meters in length and fit within the narrow envelope of quadrupole and sextupole magnets. Six of the seven copper vacuum chambers intercept significant heat loads from synchrotron radiation; five of these designs are fabricated entirely from OFS copper extrusions and are equipped with a compact Glidcop® photon absorber. A hybrid vacuum chamber, fabricated from OFS copper extrusion and a copper chromium zirconium (CuCrZr) keyhole transition, also intercepts synchrotron radiation. The seventh vacuum chamber design features a keyhole aperture across its length and is entirely fabricated from CuCrZr. This paper details the careful balance of vacuum chamber functionality, manufacturability, and the overall design process followed to achieve the final designs.

INTRODUCTION

The APS-U project is designing a storage ring upgrade that will be retrofitted to the current APS storage ring, which is composed of 40 sectors around a 1.1-kilometer circumference. By utilizing narrow aperture magnets and 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].

Design Constraints

Seven copper alloy vacuum chambers were designed to be strategically placed throughout each of the 40 storage ring sectors. The superior thermal conductivity of copper made copper alloys a straightforward material choice in regions that intercept high-intensity synchrotron radiation from the MBA lattice. Five of the seven vacuum chambers will be fabricated from copper extrusions and feature a Glidcop® photon absorber at their downstream end to shadow subsequent components that are passively cooled. Further, two of the seven designs are fully or partially fabricated from CuCrZr and feature a full or transition keyhole aperture to allow for photon extraction to bending magnet beamlines. An extrusion-based vacuum chamber design and keyhole vacuum chamber design are shown in Fig. 1.

*Work supported by the DOE under contract No. DE-AC02-06CH11357
† omulvany@anl.gov

The final assemblies primarily utilize oxygen-free with silver (OFS) copper (UNS C10700), Glidcop® Al-15 (UNS C15715), and/or CuCrZr (UNS C18150) depending on the individual requirements of the vacuum chambers. In addition, each vacuum chamber is also equipped with stainless steel flanges and water fittings.

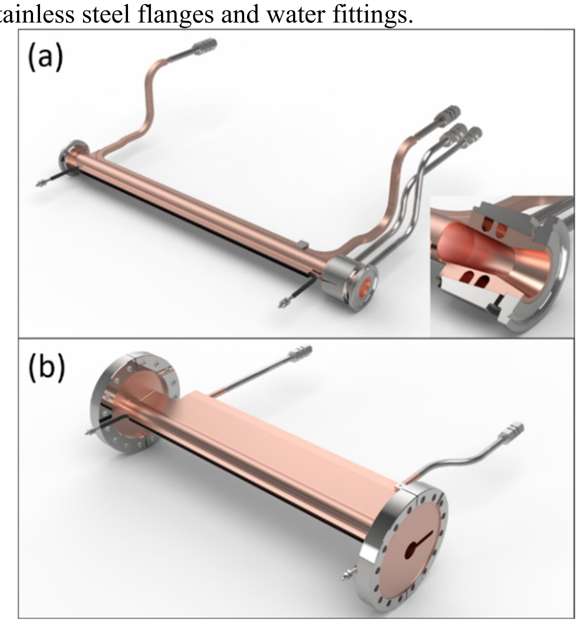

Figure 1: (a) Extrusion vacuum chamber with an inline photon absorber and (b) CuCrZr keyhole vacuum chamber.

Formal interfaces were established early in the design process of the storage ring vacuum system to ensure that the needs of each system were taken into account throughout each design phase. Interfaces with other components in the storage ring include magnets, supports, electrical systems, water systems, and other vacuum system equipment. The MBA lattice, for example, requires magnets with a narrow aperture, as seen in Fig. 2 [1].

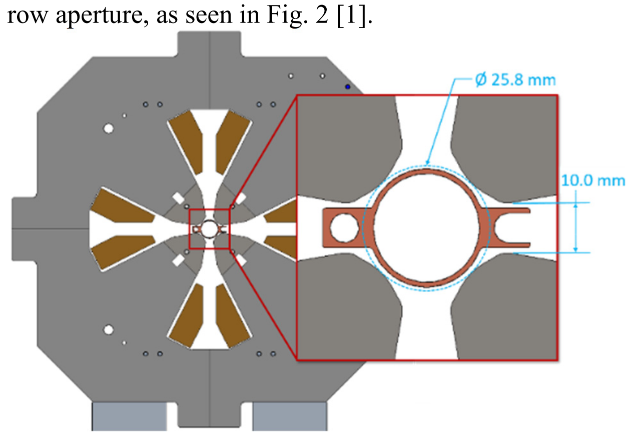

Figure 2: Typical copper vacuum chamber and magnet interface.

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-TUPLS11

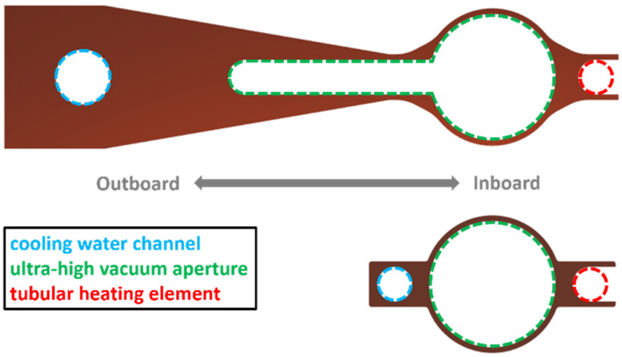

Figure 3: Keyhole and extrusion apertures.

As detailed in Fig. 3, each copper vacuum chamber features three channels that run along its length: the outboard channel is used for circulating cooling water during machine operation; the central, circular channel, or in some cases keyhole channel, houses a UHV environment for stored electron beam; and finally, the inboard channel houses a tubular heating element that is uniquely sized for each vacuum chamber for an all-electric bake-out.

Each of the extrusion-based copper vacuum chamber designs, including the hybrid vacuum chamber, intercept synchrotron radiation during machine operation. The copper vacuum chambers located in the FODO module of the storage ring intercept a linear power in excess of 1,000 W/m, while the copper vacuum chambers located in the last module of the sector (DLM-B) intercept approximately 600 W/m. Detailed ray tracing showed that these linear powers translate to total powers of 0.2 kW to 2.6 kW per vacuum chamber. In comparison, other regions of the storage ring may intercept up to 160 W/m, so aluminum vacuum chambers were generally designed and employed in these regions to reduce fabrication costs [2].

PHASES OF DESIGN

The copper vacuum chambers for APS-U went through two phases of prototyping prior to their final design iteration. One of the primary goals of prototyping was to establish a dependable design and manufacturing process that would succeed during machine operation, as the copper vacuum chambers are exposed to significant thermal loads.

Initial Prototyping Phase

Given that most copper vacuum chamber designs are struck by synchrotron radiation along the cooling water channel wall at the mid-plane, maintaining the structural properties of copper at this wall during manufacturing is critical for machine operation.

The initial design phase featured an e-beam welded cooling water channel along the length of the vacuum chamber, as seen in Fig. 4. E-beam welding was utilized for its minimal heat input, resulting in localized annealing of the material. Two vendors tested this design and after altering the weld joint geometry and introducing manual correction during the e-beam weld process, were able to complete the weld with no visible damage. Metallurgical evaluation, however, showed that the synchrotron radiation-struck surface became fully annealed in a limited area due to the heat-affected zone of the e-beam weld. Through a series of thermal-structural analyses, it was determined that the thermal stresses experienced in this region during machine operation are too high when the material is fully annealed, leading to the secondary phase of design.

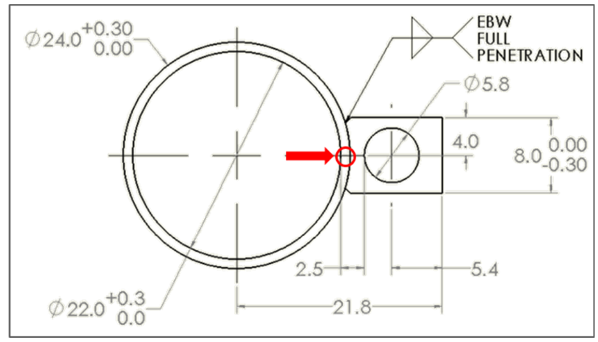

Figure 4: Electron-beam welded vacuum chamber cross-section with radiation-struck wall circled in red.

Secondary Prototyping Phase

At the suggestion of one of the vendors that tested the e-beam welded vacuum chamber, the idea of "triple-hollow" copper extrusions, whose cross-section is seen in Fig. 5 was explored as a promising alternative. The fabrication of the triple-hollow copper extrusions was presented as a two-step process; first the copper is extruded to the approximate dimensions required and then the extrusions are cold-drawn to the final dimensions in a work-hardened condition. To ensure these extrusions would meet dimensional and performance requirements, very thorough dimensional inspection, mechanical testing, and metallurgical evaluation were completed.

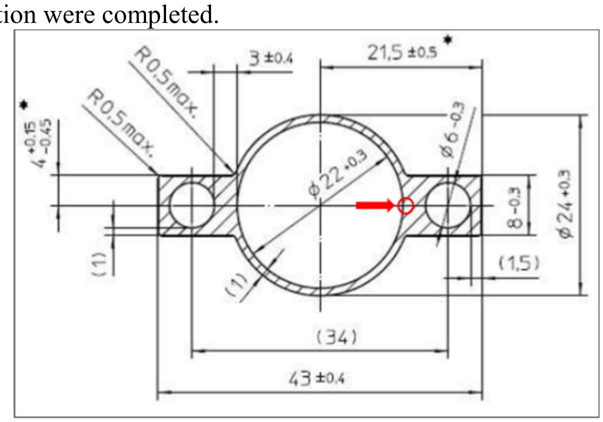

Figure 5: Extruded cross-section with radiation-struck wall circled in red.

The copper extrusions were validated by analyzing a number of samples to ensure the extrusions could meet design requirements. Dimensional inspection showed that the cross-section geometry, seen in Fig. 5, proved to be very accurate and consistent across the 3-meter long extrusions. Through use of correlations relating Vickers hardness to yield strength and ultimate tensile strength, micro-hardness testing proved that the material strength exceeded design requirements and the vendor's rated material strength [3]. Detailed metallurgical investigation could not find any

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-TUPLS11

material defects that may have led to material failure or the development of vacuum leaks. Finally, the surface roughness of the central vacuum housing was found to be well below the APS-U requirement of 1.5-micron RMS [1].

Three of the six extrusion-based vacuum chamber designs are curved to fit between magnet pole tips, so further evaluation was completed to ensure stretch-forming of these extrusions would not compromise the structural integrity or internal dimensions of the extrusions. Stretch-forming led to a small reduction in the inner and outer diameter of the central vacuum housing, but was not significant enough to compromise the extrusions. Additionally, though the material strength was remarkably higher than anticipated, stretch-forming led to no visible damage on the extrusions, meaning the ductility was not significantly impacted after being cold-drawn.

The extensive testing and analysis of the copper extrusions indicated that the extrusions are suitable for use in the final design of the vacuum chambers if carefully prescribed fabrication steps are followed during production.

Final Design Phase

Three styles of copper vacuum chambers exist in the APS-U storage ring vacuum sector arcs. Figure 1a shows the heavily tested and evaluated extrusion-based design, which accounts for five of the seven copper vacuum chambers; these vacuum chambers feature a Glidcop® inline photon absorber and vary in length from 0.3-meters to 1.7-meters. A hybrid vacuum chamber, shown in Fig. 6, is a half-extrusion and half-CuCrZr keyhole transition design and is approximately 1-meter in length. The third style of vacuum chamber, seen in Fig. 1b, is a CuCrZr keyhole photon extraction vacuum chamber and is approximately 0.5-meters in length. The two keyhole vacuum chambers utilize CuCrZr for its high strength and ability to machine a UHV-sealing knife-edge directly into the material, limiting the number of joints that require high-temperature joining operations.

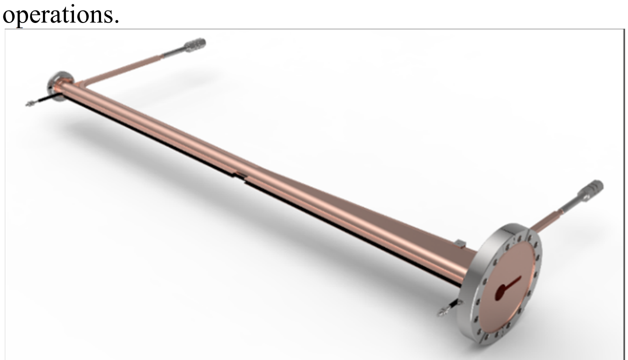

Figure 6: Hybrid copper vacuum chamber featuring a half-extrusion, half-keyhole transition design.

Similar to the two prototyping phases, extensive thermal and structural analyses were performed on final vacuum chamber designs to simulate the various conditions that each vacuum chamber would experience during its lifetime; these include machine operation which may lead to high thermal stresses, and bake-out which has the potential to cause buckling of vacuum chamber walls and annealing if bake-out temperatures are not closely monitored.

Final production of the vacuum chambers will utilize various manufacturing processes including: machining of vacuum chamber bodies by conventional means and electrical discharge machining (EDM); bending of vacuum chambers as required by three designs; joining by means of e-beam welding, furnace brazing, and torch brazing; and finally, a NEG-coating operation. NEG coating is employed across approximately 40% of the entire storage ring vacuum system, including each of the seven copper vacuum chamber designs; this is a similar NEG coating scheme to the MAX IV storage ring NEG coating scheme [4]. The copper vacuum chambers will be activated at 180°C to capture as much NEG performance as possible, while also limiting the risk of overheating magnets across the narrow installation gaps. Maintaining UHV cleanliness is essential to the performance of each vacuum chamber, so critical measures are required throughout fabrication. Additionally, quality assurance (QA) measures will be strictly followed throughout each stage of manufacturing to assure each vacuum chamber is appropriately fabricated and meets all dimensional and performance requirements.

CONCLUSION

After a complex copper vacuum chamber development process involving three distinctive phases of design, prototyping, analysis, and rigorous internal and external design reviews, the copper vacuum chamber have recently gone through a formal bidding process. The procurement process is currently underway, with future steps including fabrication, testing, QA sampling, assembly, and finally, installation into the storage ring.

ACKNOWLEDGEMENTS

The Advanced Photon Source is a U.S. Department of Energy (DOE) Office of Science User Facility operated for the DOE Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357.

REFERENCES

[1] APS-U *et al.*, "Advanced Photon Source Upgrade Project Final Design Report," APS, Illinois, United States, Rep. APSU-2.01-RPT-003, May 2019.

[2] J. Carter, "3D Numerical Ray Tracing for the APS-Upgrade Storage Ring Vacuum System Design," in *MEDSI 2018*, Paris, France, June 2018, pp. 312-315. doi:10.18429/JACoW-MEDSI2018-THOAMA05

[3] S. C. Krishna, N. K. Gangwar, A. K. Jha, and B. Pant, "On the Prediction of Strength from Hardness for Copper Alloys," *Journal of Materials*, vol. 2013, Article ID 352578, 6 pages, 2013.

[4] P. F. Tavares *et al.*, "Status of the MAX IV Accelerators," in *Proc. 10th Int. Particle Accelerator Conf. (IPAC '19)*, Melbourne, Australia, May 2019, pp. 1185-1190. doi:10.18429/JACoW-IPAC2019-TUYPLM3