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VACUUM PUMPING CROSSES AND KEYHOLE VACUUM CHAMBERS FOR THE APS-UPGRADE STORAGE RING VACUUM SYSTEM*

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Abstract

The Advanced Photon Source Upgrade (APS-U) storage ring arc consists of a diverse system of narrow-aperture chambers in compact magnet assemblies with gaps often less than 1 mm. The vacuum system contains two stainless steel pumping crosses and two keyhole-shaped vacuum chambers, as well as eight non-evaporative getter (NEG) coated aluminum chambers and crosses per sector (40 total sectors). Each chamber contains a 22 mm diameter electron beam aperture and the keyhole components also feature a photon extraction antechamber. Each design balances functionality, manufacturability, and installation needs.

The design process was aided by a flexible CAD skeleton model which allowed for easier adjustments. Synchrotron radiation heat loads applied to inline chamber photon absorbers and photon extraction beam envelopes were determined via a 3D ray tracing CAD model. The inline photon absorber and the keyhole shapes were optimized using iterative thermal-structural FEA. Focus was put on mesh quality to model the <0.5 mm tall synchrotron radiation heat load absorbed across the length of the chamber to verify cooling parameters. The design process also required careful routing of the water system and vacuum pumps. The designs incorporate beam physics constraints of the inline absorbers, cross-housed discrete absorbers, and pumping slots.

The group of chambers require complex manufacturing processes including explosion bonding, EDM, NEG and copper coating, extruded and drawn tubing, e-beam welding, challenging TIG welding, UHV cleaning, and critical dimensional measurements. The 528 chambers entered the production phase starting in 2019 with some design evolution reflecting the vendors' capabilities. This paper details the design, analysis, and manufacturing of these chambers.

INTRODUCTION

The APS-Upgrade (APS-U), when completed, will have a 6 GeV, 200 mA 1.1 km storage ring with a brightness greater than 4 keV. The storage ring consists of a diverse set of vacuum chambers including, but not limited to two stainless steel (SST) keyhole chambers, two specialty SST pumping crosses, and eight non-evaporative getter (NEG) coated aluminum vacuum chambers and crosses per sector (40 total sectors). The vacuum system also features NEG-coated copper and Inconel chambers, aluminum L-bend chambers, discrete photon absorbers, and beam position monitors with RF-lined welded-on bellows [1, 2]. Generally, all chambers house the electron beam within a Ø22 mm aperture, often with a minimum ~1 mm wall thickness and magnet gap <1 mm. An example of an aluminum cross is shown in Fig. 1.

Figure 1: Rendering of the NEG-coated aluminum pumping cross; chamber lengths range from 289 mm to 792 mm.

The SST keyhole chambers feature an extended outboard aperture to serve in the photon extraction scheme as shown in Fig. 2.

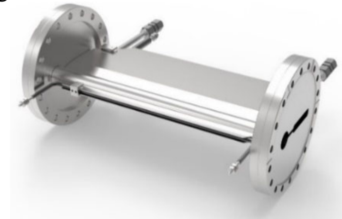

Figure 2: Rendering of a SST keyhole vacuum chamber; chambers lengths range from 305 mm to 350 mm.

The specialty SST crosses (Fig. 3) adapt similar concepts from the keyhole and aluminum chambers. The more complex A:VC6 cross houses a discrete crotch photon absorber and branches the photon extraction away from the electron beam.

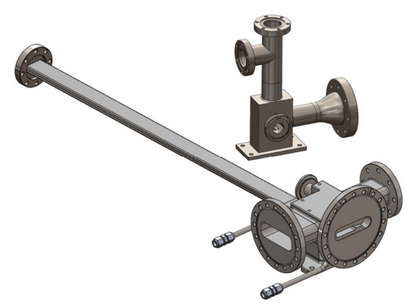

Figure 3: Rendering of the two specialty SST crosses (A:VC15 on top and A:VC6 on the bottom).

INTERFACES

All chambers interface with the following systems: magnets, water circuits, electrical bakeout system, and other vacuum components. The primary design constraint is the narrow space envelope allowed within the quadrupoles and sextupole magnet bores. Figure 4 and Fig. 5 highlight the common constraints.

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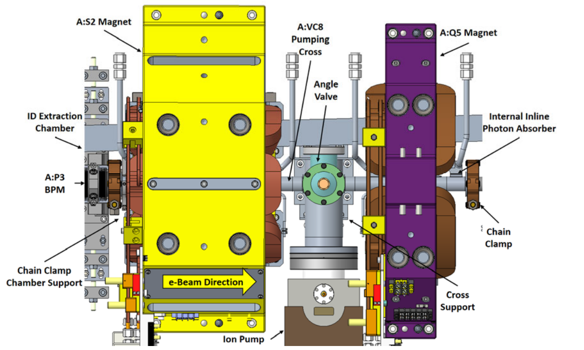

Figure 4: Top view of an aluminum pumping cross within a sextupole (left) and quadrupole (right) magnet.

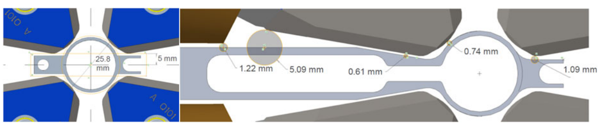

Figure 5: Cross-sectional view of an aluminum chamber (left) and keyhole chamber (right) within a quadrupole magnet.

The second space constraint, especially for the keyhole chambers, is the stay clear space envelope designated for the electron and photon beams. A ray tracing layout was created in tandem with a CAD skeleton model as shown in Fig. 6. This allowed the ability to map heat load footprints of synchrotron radiation as well as have the flexibility to adjust design parameters while the ray tracing automatically updates. This system approach influenced the design of many storage ring components to carefully adjust heat loads and shadow sensitive components [3].

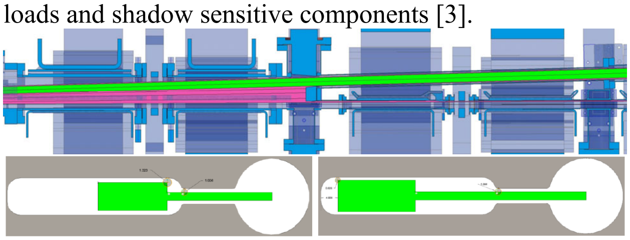
Figure 6: Top cross-sectional view of the ray trace through several chambers (top, beam direction from left to right), upstream (L) and downstream (R) cross-sectional view of the beam envelope (in green) within the keyhole chambers.

The A:VC6 cross houses a discrete crotch photon absorber within the main body as shown in Fig. 7. The pocket follows the contour of the absorber with a 1 mm gap to balance considerations for impedance and arcing concerns.

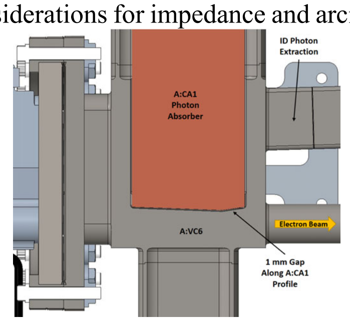

Figure 7: Top cross-sectional view of the discrete photon crotch absorber within the A:VC6 cross body.

DESIGN AND FABRICATION

The final design of the NEG-coated Al cross is shown in Fig. 8 after prototyping and consideration for manufacturability. The cross consists of a standard chamber on the upstream side, central body with venting slots, and a standard chamber with an inline photon absorber machined into the downstream flange. The chamber bodies are a three-cavity 6063 Al extrusion with the Ø22 mm beam aperture in the center and two flanking Ø5 mm channels for outboard water cooling and inboard in-situ bakeout heaters. All flanges are 316L SST/2219 Al bimetal. The flanges along the beam path are SST Quick ConFlat (QCF) which seal via space saving chain clamps and custom copper RF sealing gaskets common across the APS-U storage ring. The Al chambers are NEG coated after fabrication to reduce outgassing and add distributed pumping. Ion pumps and NEG-coated chambers provide the pumping for the conductance-limited vacuum system. Considerable effort was made to produce a compact water-cooling scheme to the inline absorber while fitting in the narrow space envelope and ensuring the parts could be welded [4].

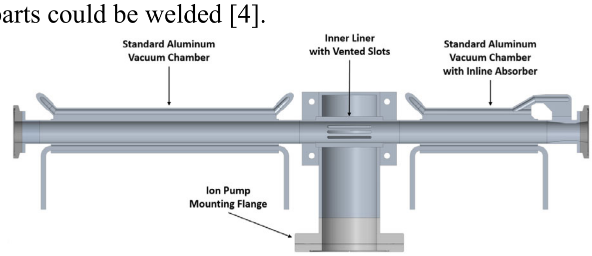

Figure 8: Top cross-sectional view of a NEG-coated Al cross.

A few minor design changes were implemented into the production parts after the completion of fabrication samples. The most considerable change was to the saddle weld joint between the cross body and vented tube. The joint was converted into a butt weld joint to achieve consistent full penetration welding, which eliminated the risk of trapped cleaning fluids compromising the NEG-coating process.

The design of the 316LN SST keyhole chamber is shown in Fig. 9. Generally, the design was driven by the tight interfaces with the magnets and beam envelope as well as mechanical stresses during operation [4]. Similar to many of the other vacuum chambers, it features outboard water cooling and a pair of bakeout heaters. Two heaters are necessary due to the poor thermal conductivity of SST.

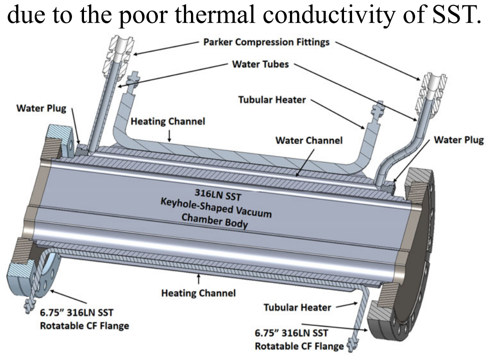

Figure 9: Top cross-sectional view of a SST keyhole chamber.

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The final design required the chamber body to be fabricated via wire EDM and the flanges brazed to the ends. The chamber is completed after an electroplated copper finish is applied to the entirety of the aperture [4]. Since the start of production, the design has been updated to accommodate a vendor preferred fabrication approach. The chamber body exterior is milled and the interior is wire electrical discharge machined (EDM). The flanges are e-beam welded along a racetrack-shaped path perpendicular to the flange face. The flange is then machined flat. The A:VC6 cross utilizes this joint design for a nearly identical application. Thus far, this joint has been proven reliable from vendor performed leak tests and residual gas analysis.

The more complex A:VC6 specialty SST cross is shown in Fig. 10. The design shares a few aspects with the keyhole chambers (the aforementioned e-beam weld joint for one flange and copper electroplated interior). The cross body is the most complex component which requires careful EDM to produce the absorber pocket. The welded-on photon extraction chamber design originally consisted of two bent sheet metal halves with a longitudinal e-beam weld. Since production, most of the extraction chamber bodies are formed via drawn tubing. The SST A:VC15 cross (Fig. 3) shares many commonalities with the central body of the aluminum chambers.

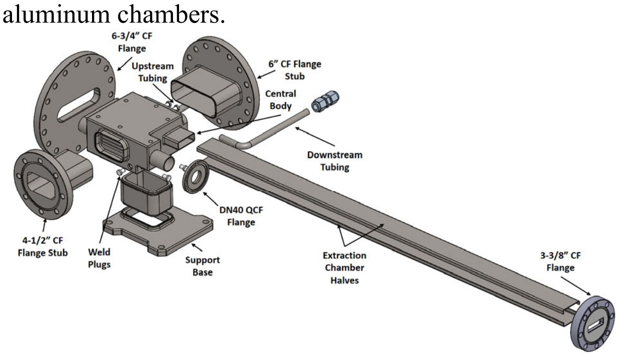

Figure 10: Exploded view of the A:VC6 cross design.

FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) was extensively utilized to develop the final chambers designs. Chambers were analyzed under operating conditions, bakeout conditions, and tested for buckling. The overall strategy required model partitioning to optimize mesh quality for thin walls and beam heat load footprints. In the case for the larger crosses, submodeling was used to more efficiently analyze large models with sub-millimeter sized heat load applications. In the case of analyzing the chambers during operating conditions, a coupled thermal-structural set-up was used with a turbulent water-cooling convective heat transfer coefficient applied to the water channel and synchrotron heat loads applied on the beam footprint along the outboard surfaces. Figure 11 shows the hottest Al cross with 98 W and a max temperature of 83.7°C on the inline photon absorber. Atmospheric and water pressure as well as mechanical constraints were applied to the structural analysis. The resulting maximum stress (46.3 MPa) occurs on the aluminum part of the inline bimetal absorber as shown in Fig. 12.

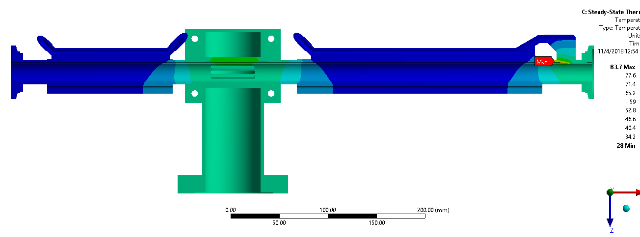

Figure 11: Top cross-sectional view of temperature results of the pumping cross FEA (max temperature of 83.7°C).

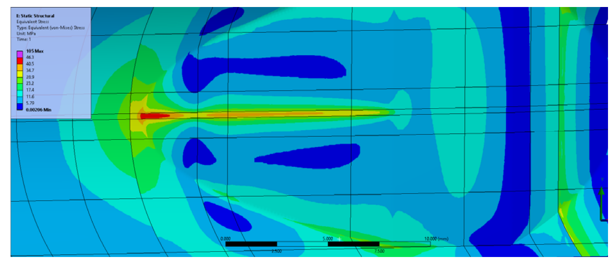

Figure 12: Von-Mises stress results on the inline photon absorber (maximum stress 46.3 MPa).

In addition to thermal-structural analysis, the thin-wall SST keyhole and rectangular extraction chambers were analyzed for buckling due to the wide non-circular aperture. An example shown in Fig. 13 demonstrates that the keyhole chambers' critical load is approximately 328 atm. The buckling model is kept simple with a 4 mm thick (in x) sliver since vertical collapse would be the most reasonable mode for buckling to occur.

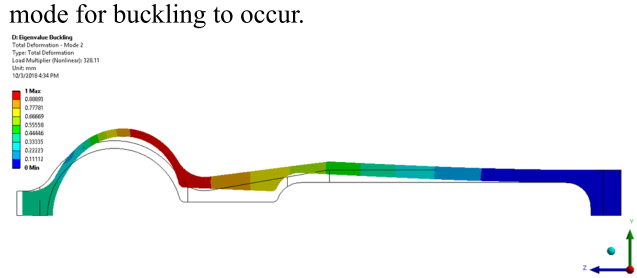

Figure 13: Critical load found to be 328 atm from buckling FEA for the keyhole chambers.

CONCLUSION

The APS-U is confident with the expected performance of the components presented in this paper. All components have been extensively designed, analyzed, and reviewed. At the time of this publication, most first article chambers have arrived at the APS with the production batches expected through 2022.

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