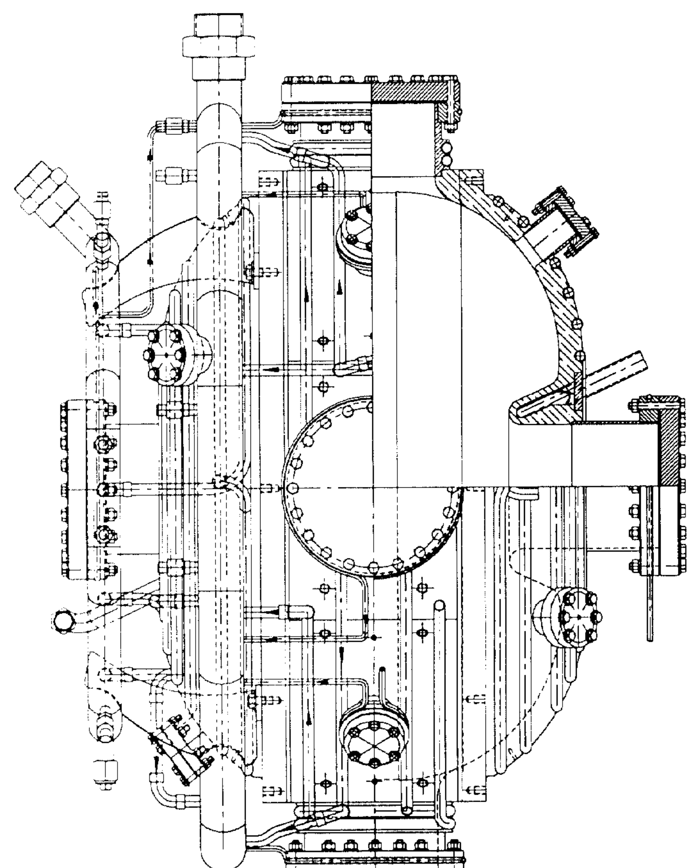
Fabrication of the APS Storage Ring Radio Frequency Accelerating Cavities

K. Primdahl, J. Bridges, F. DePaola, R. Kustom, D. Snee[1]
Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439

Abstract·

Specification, heat treatment, strength, and fatigue life of the Advanced Photon Source (APS) Storage Ring 352-MHz radio frequency (RF) accelerating cavity copper is discussed. Heat transfer studies, including finite element analysis, and configuration of water cooling is described. Requirements for and techniques of machining are considered. Braze and electron beam joint designs are compared. Vacuum considerations during fabrication are discussed.



APS Storage Ring RF Accelerating Cavity
(water manifolds removed on one side)

I. INTRODUCTION

The 7-GeV Advanced Photon Source positron storage ring will require sixteen separate 352-MHz RF accelerating cavities. Cavities will be installed, four each, in straight sections used elsewhere for insertion devices. Specifically, the RF cavities will occupy the first such straight section after injection, along with the last three just before injection. Power is supplied via waveguide from an adjacent building, with a coupling loop incorporating a cylindrical ceramic window. A single tuning plunger will be provided. Cavity beamline aperture of 140 mm (5.512 in) was chosen to limit cavity area subject to synchrotron radiation.

Cooling will be provided by a closed loop system, exchanging heat with the APS chilled water system. Water skids will be located in the adjacent klystron building, yet as close to the cavities as is reasonable. Vibration will be minimized by mounting the pumps on cushioned concrete bases. A 400 liter/sec ion pump with a lumped-non-evaporative-getter will be installed on a drop line adjacent to each cavity. The vacuum tube-cross to the drop line allows for independent alignment of each cavity, and is designed for low impedance to the positron beam.

II. MATERIALS

Room temperature RF cavities have been successfully fabricated of solid Oxygen Free High Conductivity (OFHC) type coppers, copper-electroplated steel, copper-clad steel, and aluminum. Important considerations include: electrical conductivity, thermal conductivity, mechanical characteristics, vacuum outgassing rate, coefficient of secondary electron emission, formability/machinability, weldability/brazeability, and cost. For the APS, Oxygen Free Electronic (OFE) copper, UNS C10100, Class 2 is specified. In specifying copper, "grade" refers to chemical content, while "class" refers to metallurgical characteristics; primarily grain size and inclusions. ASTM B170 and F68 provide the standards for grades and classes of copper suitable for RF cavities. OFE copper is at least 99.99% copper, with less than 5 ppm of oxygen. Low oxygen content is important to electrical conductivity and brazeability (hydrogen atmosphere of a braze retort will combine with oxygen to cause pitting of the surface where oxygen is present in copper). Whereas oxygen is displaced by adding phosphorus in cheaper grades of copper, no such additives are allowed for high purity copper; hence, care must be taken not to introduce oxygen during each refining/processing step. In addition, we required a vacuum degas during the casting process, an operation that removes hydrogen and is normally important only for production of Class 1 copper. The essential difference between Class 1 and 2 is hydrogen interstitials vs. void interstitials along grain boundaries.

As rough shapes for APS cavities exceed cake width ("cake" refers to a rectangular cross-section, while "billet" refers to a circular cross-section), it is necessary to forge the cast copper in order to generate a size/shape that allows APS cavities to be fabricated of three pieces: two cup-shaped ends, and one ring-shaped center. Moreover, we require that the three shapes be cross-grain forged in order to break up the grain boundaries. For high purity copper subjected to furnace brazing temperatures, grain growth can be significant; in fact, a single grain boundary through the thickness of a cavity wall is possible [1]. After cross-

* Work supported by U.S. Department of Energy, Office of Basic Sciences, under Contract W-31-109-ENG-38.

[1] Fermi National Accelerator Laboratory.

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

grain forging to width and thickness (no forming), our copper shapes were rough machined, allowing the supplier to immediately recycle a great deal of "hogged out" copper.

III. THERMAL ANALYSIS & COOLING

Important considerations for thermal performance include: thermal gradient/stress/distortion within the copper, outside to inside copper surface temperature difference, water to outside surface temperature difference, temperature rise of cooling water, total water flow rate, water velocity, and number/size/location of cooling tubes. As is typical for accelerator systems, water-to-vacuum joints are prohibited at the APS.

A two-dimensional, axisymmetric URMEL model generated the distribution of heat load on the cavity surface. Results were used as input to an ANSYS† thermal/stress analysis. Using hand-calculated convection coefficients for water flowing in copper tubes at several flow rates, and varying the numbers of tubes, several ANSYS® models were generated for comparison. Distortion of the cavity due to thermal stresses may affect the resonant frequency, a characteristic which can be used to tune the cavity, provided copper fatigue does not become critical. Enhanced heat transfer with increasing water velocity must be balanced against possible erosion corrosion where the protective layer of copper oxide on the inside wall of copper tubes is stripped away, leaving the soft copper subject to erosion by flowing water (especially at the outer edge of a formed elbow, where the wall has already been thinned by forming). The final design is optimum in that: temperature differences are within the range of a conventional water cooling system, water velocity can be held to a range where erosion corrosion of the copper tubes is not a concern, thermal gradient/distortion within the copper is not severe, and fabrication/attachment of cooling tubes is straightforward.

In the final design, a nose-cone cooling channel is milled into each end piece from the outside (sealed with a brazed cover), and twenty 12.7-mm-diameter (0.5-in) copper tubes are brazed into milled channels (slightly deeper than half the tube diameter). Measurements taken on a prototype cavity with 19.0-mm (0.75-in) tubes, where thermal contact was suspect, showed that tubes with only half their diameter embedded in the bulk copper are capable of approximately 93% of the heat transfer of fully embedded tubes as predicted by Dittus-Boelter [2]. Finally, we selected copper tube extruded with rifling on its inside surface to increase turbulence and surface area. Total flow of 4736 cm^3/sec (75 gpm) will be supplied in an all parallel arrangement, divided into three circuits. Orifice plates and thermocouples will be used to balance flows for uniform temperature rise. Average velocity will be 111 cm/sec (3.7 ft/sec), whereas the velocity above which erosion corrosion becomes a concern is reported to be 227-364 cm/sec (7.5-12 ft/sec). For the worst-case of 75-kW heat load, a 3.7 K water temperature rise will result.

Our ANSYS® thermal analysis showed maximum copper temperature to be 17° C above the water temperature. Meanwhile, the prototype cavity was found to have higher temperatures around the ports, especially within stainless steel where electrical and thermal conductivity are lower than for copper. We subsequently reduced the amount of stainless steel exposed to RF, then copper plated (pure copper) the stainless steel surfaces wherever possible (including vacuum surfaces of blank-off flanges). Furthermore, we have provided flange cooling.

Similarly, our ANSYS® stress analysis shows a peak stress intensity of 27.6 MPa (4000 psi) with non-peak stress intensity up to about half that value, in the same range as is reported for 0.2% yield strength of fully annealed copper [1]. With such a low yield strength, cycling into the plastic range seemed unavoidable; accordingly, a fatigue analysis was performed. Applying the strain-life approach showed fully annealed copper to be very accommodating: using conservative boundary conditions, a fatigue life of over 10^{24} cycles was estimated [3].

† ANSYS is a registered trademark of Swanson Analysis Systems, Inc., Houston, PA.

IV. MACHINING

Although we had first planned to hydrogen-retort-anneal the rough machined copper as a proof test against oxygen content, our fabricator preferred to machine the outside features of the cavities before annealing the copper (believed to be in approximately the "half-hard" state after forging). Nevertheless, inside features are machined from fully annealed copper, after brazing of the cooling tubes and cavity ports. Nearly all machining operations of the inside surface are turning operations, where tight tolerances and required surface finish are most easily achieved. Care has been taken not to introduce sulfurized (discolors copper) or chlorinated (future corrosion problems as chlorine migrates throughout a vacuum system) cutting fluids. Specifically, we allow only waterbased cutting fluids, diluted with deionized water. All tooling is prohibited from touching any vacuum surface, and aluminum prohibited from contacting any braze surface (said to interfere with wetting during brazing). End and center pieces are machined incrementally; being removed for inspection (while tooling remains in place), to allow for checking of residual stresses and machine errors, by coordinate measuring machine. Machining parameters are adjusted to accommodate small deviations.

A small amount of excess material, in the form of a circumferential step, is left during inside machining of the center section; hence, part of the inside diameter remains undersize. A set of two ends and one center are test assembled, then resonant frequency is measured. Resonant frequency is to be within ±50 kHz at 27° C. Predicting the effect of ambient temperature, electropolishing, and electron beam welding (0.5-0.6 mm shrinkage per weld), an amount by which step material must be machined away is calculated. This final machining is performed (center piece only), then resonant frequency checked again.

In order to vary higher-order modes among the sixteen cavities and thereby reduce cavity-bunch instabilities, each cavity varies in length (distance between the nose-cones) by 0.30 mm (0.012 in). This is achieved by machining each center section to a different length. We expect the effect on resonant frequency to be small and, in any event, negated by the resonant frequency testing and final machining described above.

V. BRAZING/ELECTRON BEAM WELDING

Brazing is possible in a hydrogen retort or vacuum oven. A hydrogen retort offers a reducing atmosphere; however, the dew point must be controlled according to the types of oxides present. Temperature vs. dew point data is available in the literature: copper oxide is relatively easy to reduce, chromium oxide (stainless steel) less so [4]. In fact, for the lower temperature filler metals, chromium oxide will not reduce—in these situations stainless steel is usually nickel plated before brazing. Alternatively, this characteristic can be used to an advantage where fixturing is concerned (prevents adhesion of fixture to parts). Oven temperature is ramped to just below the filler melt temperature, then held while all parts come into thermal equilibrium. Temperature is then raised to just above the melt temperature for a short time. Afterwards, oven and parts are cooled with inert gas before exposure to atmosphere.

Several brazing schemes were considered where one to four brazing steps would be required. Brazing in sequence can be done with different filler metals having decreasing melt temperatures. The advantage of several steps is the ability to leak check after each braze and the ease of sending a subassembly back into the furnace for a rebraze. Nearly all braze joints are tube-into-bore, where we show 0.025-0.076 mm (0.001-0.003 in) clearance, inside to outside diameter.

The part-line is 645 mm (25.4 in) in diameter at the inside edge; hence we considered it the most challenging joint. Although we originally planned to braze this joint, we later concluded that an electron beam weld, performed at the cavity fabricator's facility using a cryo-pumped weld chamber, is superior. The electron beam weld is from the outside; hence, a small (1.5 mm) step is machined on the part-line surfaces to serve as an electron beam stop. Trial welds were necessary to determine welding parameters so that the melt zone extends to the stop, but not through to the cavity (where surface irregularities and spatter would result). It should be noted that the small part-line "crack" closes during weld cooling/shrinking resulting in a smooth surface for RF currents, but prohibiting the future use of any cleaning solutions. As electron beam welding is the final fabrication step, we expect that rigorous cleaning will never again be required.

VI. ELECTROPOLISHING

In order to enhance vacuum performance, APS cavities will be electropolished after resonant frequency testing and final machining, but before electron beam welding. In one sense, electropolishing can be thought of as an aggressive cleaning procedure—it removes surface oxides, hydroxides, etc. A metal typically has a residual level of contaminant throughout the bulk, and a higher level at the surface. Though the residual levels cannot be "cleaned away," the surface level can be reduced significantly, allowing outgassing to more quickly decay to residual level. Electropolished surfaces are denser and smoother (less effective surface area); hence, can recover faster from venting to atmosphere. Similarly, smoother surfaces have lower field emission. We expect less arcing, faster conditioning, and less sputtering/migration of copper as a result of electropolishing [5].

Though electropolishing of our first end and center section subassemblies has not yet been performed, a copper/copper-plated-stainless-steel port subassembly has been successfully electropolished, insuring that electropolishing of copper-plated stainless steel can be performed without complication.

VII. ACKNOWLEDGMENTS

We express our appreciation to D. Dasbach, E. Klein, and H. Vogel, Siemens AG, Köln, Germany for their technical assistance and timely communication. Also, to T. Smith, D. Voss, E. Wallace, APS, for their extraordinary efforts in preparation and testing our prototype cavity and to L. Morrison for his perseverance with drawings and revisions. Finally, to D. Meyer, J. Maj, and C. Verdico, APS, for their assistance with thermal testing and braze development.

VIII. REFERENCES

[1] Fritz, Jim, FNAL, Personal communication with author.

[2] Incropera, Frank, and David DeWitt, *Fundamentals of Heat and Mass Transfer 2nd Ed.*, New York: John Wiley & Sons, 1985.

[3] Bannantine, Julie, Jess Comer, and James Handrock, *Fundamentals of Metal Fatigue Analysis*, Englewood Cliffs, New Jersey: Prentice Hall, 1990.

[4] Schwartz, Mel, *Brazing*, Materials Park, Ohio: ASM International, 1987.

[5] Noonan, John, Personal communication with author.