Cooling the APS Storage Ring Radio-Frequency Accelerating Cavities: Thermal/Stress/Fatigue Analysis and Cavity Cooling Configuration*

K. Primdahl, R. Kustom
Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439

Abstract

Heat transfer studies, including finite-element analysis and test results, of the Advanced Photon Source (APS) storage ring 352-MHz radio-frequency (rf) accelerating cavities are described. Stress and fatigue life of the copper are discussed. Configuration of water cooling is presented.

I. BACKGROUND

The 7-GeV Advanced Photon Source positron storage ring requires sixteen separate 352-MHz rf accelerating cavities. Cavities are installed as groups of four, in straight sections used elsewhere for insertion devices. They occupy the first such straight section after injection, along with the last three just before injection. Cooling is provided by a subsystem of the site-wide deionized water system. Pumping equipment is located in a building directly adjacent to the accelerator enclosure.

A prototype cavity was fabricated and tested where cooling was via twelve 19-mm-diameter [3/4 in] brazed-on tubes in a series-parallel flow configuration. Unfortunately, the thermal contact to some tubes was poor due to inadequate braze filler.

II. INTRODUCTION

Concerns include thermal gradient/stress/distortion within the copper, thermal stresses (a function of thermal gradients), hot spots, elastic/plastic deformation, cyclical deformation of copper, and pressure drop of water flow through the cavity. Distortion of the cavity due to thermal stresses affects the resonant frequency, a characteristic which may be used to tune the cavity, provided copper fatigue does not become critical. Keeping all the above in mind, the engineer must arrange for suitable values of the following variable parameters while incorporating the fixed parameters into the analysis and design.

Fixed parameters:

- Heat load per cavity:

7.0-GeV beam, with 16 cavities on-line	35 kW
7.5-GeV beam, with 16 cavities on-line	50 kW
7.5-GeV beam, with 12 cavities on-line	67 kW
During cavity conditioning	100 kW

- Minimum supply water temperature of 24º C.

Variable parameters (not all independent):

- Temperature of cavity copper.
- Temperature rise of the water through the cavity.
- Total flow rate of water through the cavity.
- Header size, for each section of four cavities; a practical limit of 4-inch IPS, possibly 6-inch IPS.
- Velocity of water in copper tubes. No more than 227 cm/sec [7.5 ft/sec] to avoid erosion corrosion.
- Size of cooling tubes. Surface area (heat-transfer area) scales with diameter, cross-section (inverse water velocity) with diameter squared.
- Location of cooling tubes.
- Number of cooling tubes.
- Flow configuration (i.e., series-parallel or all-parallel).
- Water supply [to cavity] temperature. Condensation is to be avoided while recirculating some return water puts less demand on site-wide deionized system.
- Heat exchanger area and temperature difference(s).

III. TUBE SIZE

Copper cooling tubes are brazed into machined channels, slightly more than half the tube diameter deep, on the cavity surface. Spreadsheet calculations determined the optimum tube size. The first two cases presented below assume effective tube area (heat transfer area) equal to 60% of the interior surface, while the second set of data employs a sliding scale that favors smaller diameter tubes (nesting the tube into a milled channel, slightly deeper than half the diameter, with a braze fillet along each side serves to "enclose" more of a smaller tube). Heat load and temperature rise of the water fix the required volume flow rate of water—resulting velocity varies with tube cross-section.

Independent Variables		Dependent Variables		
Heat Load (kW)	Temp Rise (°C)	Optimum Tube ϕ (")	Water Velocity (feet/sec)	Cu-Water ΔT (°C)
75	2.0	3/8	18.3	11.2
75	3.0	3/8	12.2	15.4
75	2.0	5/16	21.2	8.6
75	3.0	5/16	14.2	11.8
100	2.0	5/16	21.2	9.1
100	3.0	5/16	14.2	12.4

Each case shows an optimum diameter at which the copper-to-water temperature difference is a minimum. For larger diameters, surface area is not increasing fast enough to compensate for the reduction in water velocity. For smaller diameters, water velocity is not increasing enough to make up for the reduction of surface area. Moreover, enhanced heat transfer with increasing water velocity must be checked 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

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forming). Acceptable maximums are quoted, by experienced engineers, as anywhere from 227 to 364 cm/sec [7.5 to 12 ft/sec]. Our case of all parallel flow is further complicated by the fact that actual water velocity varies among the cooling tubes (the spreadsheet calculations assume uniform velocity); that is, higher velocity in the shorter tubes.

Since the velocities associated with optimum tube sizes could lead to erosion corrosion, a "practical optimum" of 12.7 mm [1/2 in] diameter was selected. Temperature rise of the water can be traded off against water velocity, but both have a wide range of acceptable values. The copper-to-water temperature difference required further study; specifically, to ensure it is within the bounds set by cavity operating temperature and cooling water supply temperature.

IV. THERMAL ANALYSIS

Using spreadsheet-calculated convection coefficients from the analysis described above, and varying the location and number of tubes on each end section, several two-dimensional, axisymmetric ANSYS[1] models were generated for comparison. A two-dimensional, axisymmetric URMEL[2] model generated the distribution of rf heating on the cavity's inside surface and was used as input to the ANSYS® thermal/stress analysis. Large ports of the center section are a non-axisymmetric feature; however, including them in an axisymmetric model is conservative since the heat that would go into solid copper if no port were present concentrates about the inside perimeter of the port. Several variations of the heat distribution about the port were evaluated; the most severe was subsequently used for the results reported here. A less severe heat redistribution is expected where a tuner or coupler, both with integral cooling, is installed.

Case	Tube-to-Water ΔT (°C)	Copper (MPa)	Max Stress (psi)
Four 3/4-in tubes	17.4	36.4	5283
Four 1/2-in tubes	18.1	33.1	4802
Four 1/2-in tubes, shifted towards "hot spots"	14.2	32.4	4699
Six 1/2-in tubes	10.7	27.8	4031

The copper-to-water temperature difference is important as the sum of all temperature rises in the water system (including across the heat exchanger), added to the water temperature, must be lower than the planned operating temperature of the cavities. Increasing the number of tubes increases the copper-to-water surface area and hence, decreases the copper-to-water temperature difference.

[1] ANSYS is a registered trademark of Swanson Analysis Systems, Inc., Houston, PA.

[2] URMEL was developed by U. Lauströer, et al., DESY, Hamburg, Germany.

The ANSYS® thermal analysis shows maximum copper temperature to be 16.9° C above the water temperature. The highest copper temperature was consistently at the port radius; however, the wall thickness there serves to keep stress low. Highest stress was observed at the tip of the nose cone cooling channel where the temperature difference between the inner wall and the 7.8-mm-thick [0.31 in] outer wall is approximately 10° C. This area could be subjected to reverse yielding. Although the change in maximum stress is small for each new model, the overall reduction is meaningful.

V. THERMAL TESTING

Measurements taken on the prototype cavity showed that tubes with only half their diameter embedded in the bulk copper are capable of approximately 93% the heat transfer of fully embedded tubes as predicted by Dittus-Boelter [1]. The Dittus-Boelter formulation is intended for internal flow in round tubes; hence, it was adapted for use on the nose-cone cooling channel's approximately rectangular 12.7 x 76.2 mm [0.5 x 3.0 in] shape. The ANSYS® heat transfer coefficients differ from theoretical values in order to be conservative (while we awaited prototype test results).

Cooling Geometry	Tube Diameter (cm [in])	Theory (W/cm^2)	Used for ANSYS® (W/cm^2)	Prototype Tests (W/cm^2)
Nose-cone		0.600	0.600	0.837
End	1.90 [3/4]	0.604	0.511	0.600
Center	1.90 [3/4]	0.604	0.511	0.566
End	12.7 [1/2]	0.915	0.604	
Center	12.7 [1/2]	0.915	0.604	

The 1.90-cm-diameter [3/4 in] tube results are based on a water velocity of 182.9 cm/sec [6.0 ft/sec], while the 12.7-cm-diameter [1/2 in] numbers are based on a water velocity of 268.2 cm/sec [8.8 ft/sec]. The ratio of these velocities corresponds to the ratio of cross-sectional areas of six 12.7-cm-diameter [1/2 in] tubes to four 1.90-cm-diameter [3/4 in] tubes; that is, the same total flow.

Meanwhile, the prototype cavity had unexpectedly high temperatures around the ports, especially in the stainless steel where electrical and thermal conductivity are lower than for copper.

VI. STRESS/STRAIN-LIFE

Our ANSYS® stress analysis shows a peak stress (total stress, reflecting nonlinear variation between endpoints) intensity of 27.8 MPa [4031 psi] with non-peak stress (membrane plus bending, varying linearly between endpoints) intensity up to about half that value, in the same range as is reported for 0.2% yield strength of fully annealed copper [2]. With such a low yield strength, cycling into the plastic range seems unavoidable; accordingly, a fatigue analysis was performed. Fatigue studies of oxygen-free copper show that the hysteresis loop for fully annealed copper increases in amplitude (constant strain) as the number of cycles increases. Conversely, the hysteresis loop of cold-worked copper falls off with increasing cycles. Hence, fully-annealed copper cyclically hardens, while cold-worked copper cyclically softens.

The more traditional stress-life fatigue analysis method does not account for plastic strain; therefore, it is inappropriate. However, the strain-life approach, where the allowable strain amplitude is calculated as an exponentially-weighted (exponents are determined empirically) sum of the elastic and plastic cyclic loading, is ideal for the cavity analysis, where knowledge of extreme temperatures leads directly to expected strain amplitude. Application of the strain-life approach [3] shows fully annealed copper to be very accommodating; using conservative boundary conditions, a fatigue life of over 10^{24} thermal cycles is estimated.

VII. FINAL DESIGN

The complete cavities are fabricated as three subassemblies, two ends and a center, which are joined by electron beam welds about the perimeter. A nose-cone cooling channel is milled into each end piece from the outside (sealed with a brazed-on cover), while twenty 12.7-mm-diameter [0.5 in] copper tubes are brazed into milled channels (slightly deeper than half the tube diameter). The final design is optimum in that: (1) temperature differences are within the range of a conventional water cooling system; (2) water velocity can be held to a range where erosion corrosion of the copper tubes is not a concern; (3) thermal gradient/distortion within the copper is not severe; and (4) fabrication/attachment of cooling tubes is straightforward. Additionally, we specified copper tube extruded with rifling on its inside surface to increase turbulence and surface area.

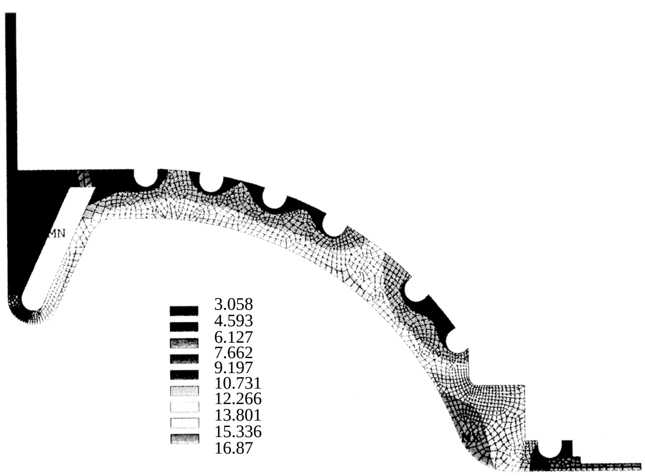

Figure 1: ANSYS® Thermal Analysis Results.
Model is axisymmetric about the beamline—a vertical line to the left of the figure.
(Degrees Centigrade above Water Temperature)

In order to minimize the flange heating found on the prototype cavity, the amount of stainless steel exposed to rf was reduced. The remaining stainless steel, including vacuum surfaces of blank-off flanges, is copper plated (pure copper). Additionally, we have provided flange cooling via 6-mm-diameter [0.236 in] copper tubes brazed into the perimeter of each flange. Furthermore, an additional tube was added to each quadrant of the center section, providing twice the cooling used in the ANSYS analysis for that area. This additional tube also provides cooling over the entire port perimeter (the prototype cavity had only 300° cooling tube coverage at each large center-section port). Accordingly, the ANSYS® results most closely resembling the final design are those of the 27.8-MPa [4031 psi] case. Figure 1 presents the temperature distribution in the cavity copper, showing a maximum copper temperature 16.9° C above the water supply temperature.

An innovative manifold arrangement allows balancing of the flows among the two ends and center, yet requires only two supply and two return manifolds. Total flow of 4736 cm^3/sec [75 gpm] is supplied in an all parallel arrangement, divided into three groups: center section, end sections, and nose-cones. Orifice plates balance flows among the groups for uniform temperature rise. Within each group are several parallel flows balanced only by uniform pressure drop. Average velocity is 111 cm/sec [3.7 ft/sec]. Since tube lengths are not identical, while pressure drop across the cavity is essentially uniform, actual velocities vary. Calculations for the six end-section tubes show that relative velocities are expected to range up to ± 32% of average velocity.

For the case of 75 kW and 75 gpm, a 3.7° C water temperature rise and a copper-to-water temperature difference of 9° C are expected. A minimum copper temperature occurs on the back side of the nose-cone cooling channel where the heat load is nearly zero; hence, the copper temperature closely matches the water temperature. For these conditions, temperatures throughout the system are expected to be:

Planned water supply temperature	32° C
Copper tube temperature	41° C
Average copper temperature	43° C
Maximum copper temperature	49° C
Water return temperature	36° C

Cavities were required to meet resonant frequency specifications when tested at the planned operating temperature; actually, we adjusted for testing at a lower, uniform copper temperature. Final measurements show a variation of -21 kHz to +43 kHz in cavity resonant frequencies. Measurements show a temperature dependence of -3.6 kHz/° C. In light of the fact that piston tuners fabricated for the cavities have a tuner range of approximately 2 MHz, one concludes that actual water supply temperature is not critical. The thermal time constant for the cavity alone, with 75 gpm flow of cooling water, is 30 seconds.

VIII. REFERENCES

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[3] J. Bannantine, J. Comer, and J. Handrock, Fundamentals of Metal Fatigue Analysis, (Prentice Hall, Englewood Cliffs, New Jersey, 1990).