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DEVELOPMENT OF LOW VIBRATION COOLING SYSTEMS FOR BEAM-LINE OPTICS USING HEAT PIPE TECHNOLOGY

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Abstract

Cooling of in-vacuum beamline components has always been problematic. Water cooling lines can transfer vibrations to critical components, and often require complex air guarding systems to ensure that the vacuum envelope is not breached in the event of a leak. These constraints increase design complexity, limit options, and provide challenges for assembly and maintenance.

Commercial heat pipes are inexpensive and readily available. Custom assemblies can be fabricated into vacuum flanges and may use non-water-based cooling mediums if required. A mockup of an optical assembly has been used to explore vibration reduction and cooling capacity. Other example beamline components such as a heat generating electromagnetic shutter, demonstrate the cooling capability of these heat pipes.

INTRODUCTION

A heat pipe [1] [2]is a device with a very high thermal conductivity that can transport large thermal loads. It is a passive, 2-phase device that comprises a sealed tube at sub-atmospheric pressure that contains a wicking medium and a working fluid. (Figure 1) At the hot end the working fluid absorbs energy and evaporates. It then migrates to the cold end where the thermal energy is released and the fluid condenses. The wicking material draws the condensed liquid back to the hot end. With proper design, the device can generally operate in any orientation, but if vertical with the hot end elevated, then gravity will help with the wicking.

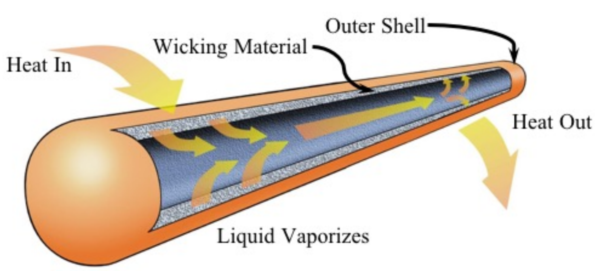

Figure 1: Heat Pipe Operation.

Table 1 lists thermal conductivities of various metals used in vacuum systems and the conductivity of a typical heat pipe. Heat pipes have an extremely high effective thermal conductivity compared to a solid metal conductor of the same size/shape ~x10-100. Internal design, orientation and working temperatures as well as heat loads need to be considered for proper selection. [3] [4] Operation ranges can be anywhere from cryogenic to over 1500º C, and determine both the working fluid and outer shell. For 0-100º C operations water with a Copper shell is the most common and was used for these tests. Ethanol, methanol, and acetone can also be used. For use in UHV environments, sealing methods and materials are a factor. [5] This paper examines the suitability of heat pipes for cooling in-vacuum components on beamlines and endstations.

Table 1: Thermal Conductivities of Materials

Material	Conductivity (W/m•K)
Heat Pipe	10,000 +
OFHC Copper	390
6061 Aluminum	167
304 Stainless Steel	16.2

VACUUM COMPATABILITY

Standard Commercial Off The Shelf (COTS) heat pipes are typically fused and sealed by friction welding at the filled end. This end seal is the main potential point of failure that could result in leaking the working fluid into the vacuum. To determine vacuum suitability, two commercial heat pipes were ultra-high vacuum (UHV) cleaned and placed in a testing chamber that was then baked at 180º C for 2 days. Before and after bake residual gas analysis (RGA) scans were performed and after removal they were tested by placing them in a cup of hot water where they performed as expected.

Another heat pipe was cut in two and brazed onto a standard 2.75” Conflat flange so that the sealed ends of the pipe would be exposed to vacuum. (Figure 2) This was then UHV cleaned and mounted in a testing chamber equipped with an RGA. The assembly was exposed to repeated 180º C bake cycles of 24 hours with RGA scans performed after each cycle.

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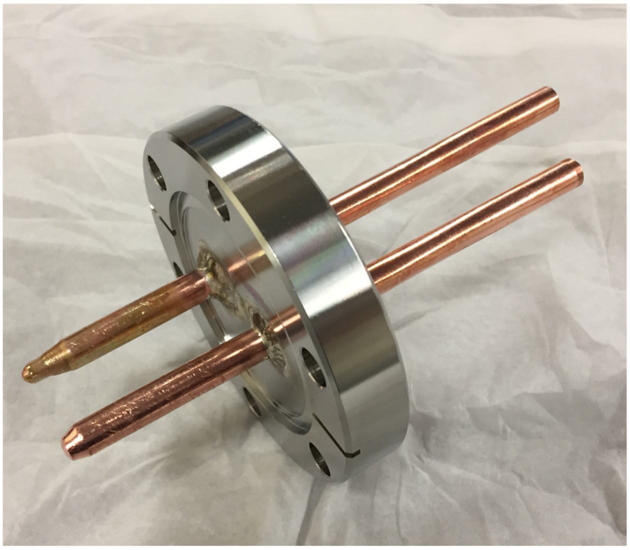

Figure 2: Heat Pipe Vacuum Test Assembly.

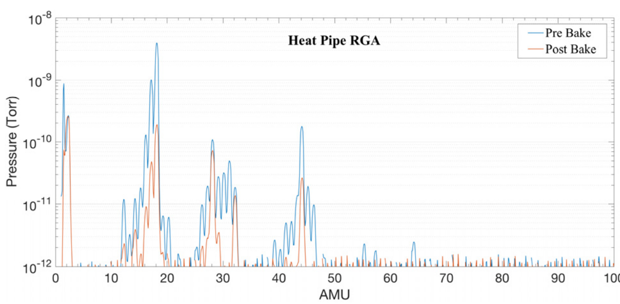

Figure 3: Heat Pipe RGA Scan.

The assembly was monitored for 5 bake cycles and no signs of leaking or contamination were found as indicated by a clean UHV RGA scan (Figure 3). It was then left on the testing chamber during testing of other UHV components for approximately another 15 cycles over 2 months. No signs of leaking were found which implies that for this heat pipe at least, the friction vacuum seal of the heat pipe is adequate for normal UHV practices.

THERMAL TESTING

In these tests, a 457mm long, 6.35mm dia. heat pipe was fabricated into a 2.75" Conflat flange (Figure 4). The in-vacuum end was coupled to an Aluminum block to represent a generic optic, and an Aluminum cold plate connected to a chiller was attached to the air end of the heat pipe. Indium foil was used to ensure good thermal contact. A 20W Kapton foil heater was placed on one face of the Aluminum block to represent X-Rays impacting the face.

For testing, the system was mounted in a vacuum chamber (Figure 5) and pumped to high vacuum (~1e^{-6} Torr) to remove any convection effects. The chiller was set to 18° C and power was applied to the heater to output 20 W. After reaching thermal equilibrium, temperatures on the optic face, and both ends of the heat pipe were recorded and compared to thermal finite element analysis (FEA) that was conducted based on the manufacturers specifications for the operating conditions. Figure 6 shows the thermocouple locations about the heated Aluminum block. Figure 7 shows the FEA of the system in thermal equilibrium. Table 2 shows the FEA and measured temperatures.

The FEA agrees reasonably well with the measurements – the heater block temperatures are within 5° C and the heat pipe within 2° C. Refining the thermal contact at the joints for the FEA would be needed for closer agreement.

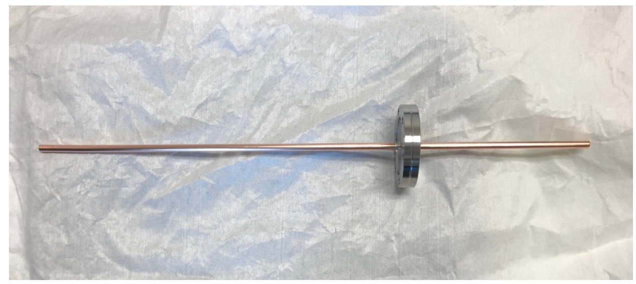

Figure 4: Custom Heat Pipe in CFF Flange.

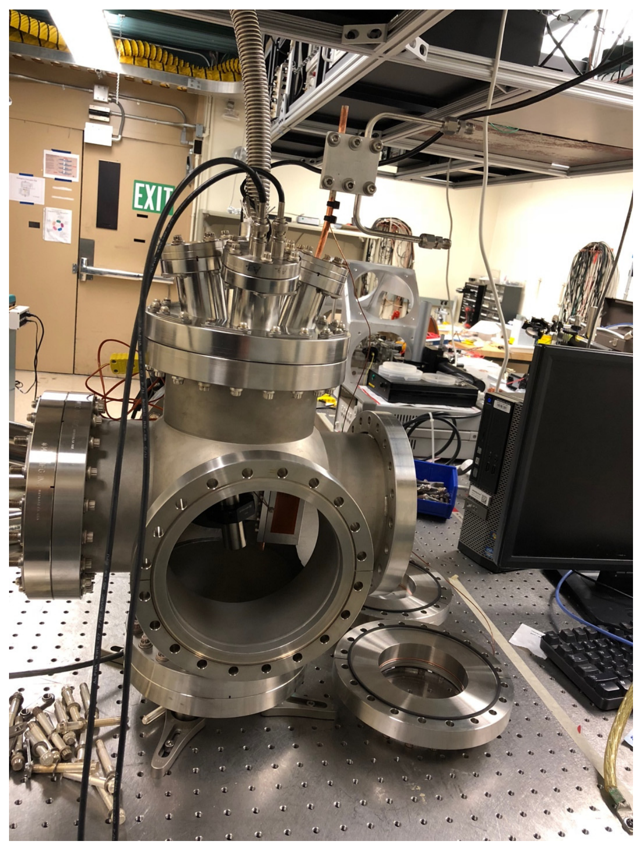

Figure 5: Test Chamber Assembly.

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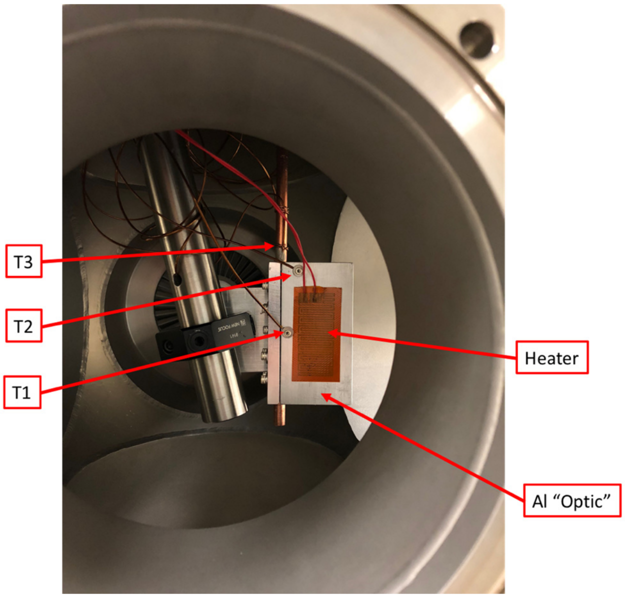

Figure 6: Al heater block and in-vacuum thermocouples.

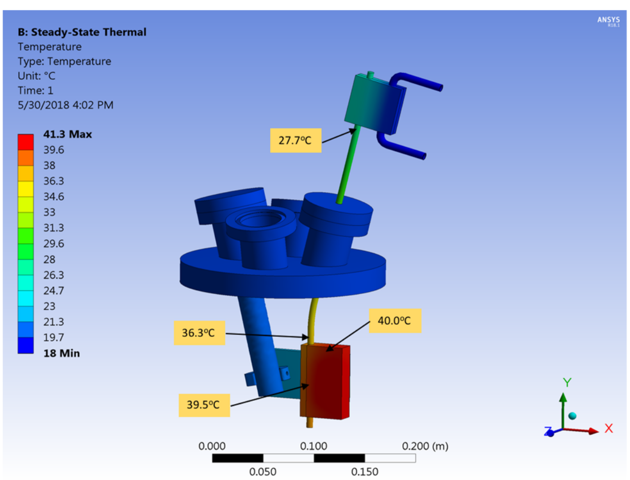

Figure 7: Thermal FEA.

Table 2: FEA Comparison to Measured Values in Figure 6 and Figure 7

Temperature	FEA	Measured
T1 – Al Block	39.5 °C	45.6° C
T2 – Al Block	40.0 °C	44.7° C
T3 – HP Base	36.3 °C	37.1° C
T4 – HP Top	27.7 °C	25.8° C

VIBRATION MEASUREMENTS

Accelerometers were mounted on the Aluminum heater block (Figure 8) and vibration measurements were taken with for various combinations of cooling water on, off and for the water cooling section directly coupled to the Aluminum heated block.

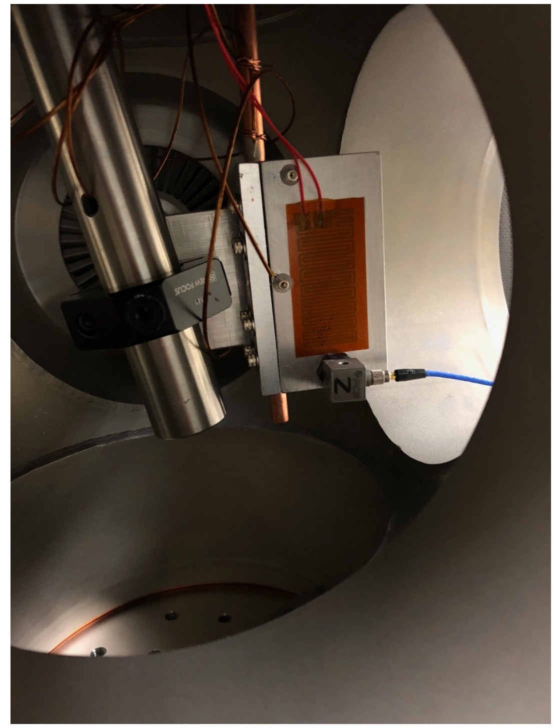

Figure 8: Test Assembly with Accelerometer.

Figure 9 shows the Power Spectrum Distribution (PSD) in the X, Y, and Z axis on the cooling block with the heat pipe attached and the cooling water on/off. The plots indicate slightly increased vibrations with the water flow on.

Figure 10 compares the PSD between the cooling block and the heater block, i.e. between the two ends of the heat pipe with cooling water on. The cooled end is fairly unconstrained and vibrations from the cooling water are greatly amplified at this end, but do not translate through to the hot end. This indicates good vibrational decoupling between the two.

Figure 11 compares the PSD of the Aluminum heater block with both the heat pipe installed and with the water directly coupled to the heater block. In both cases the cooling water on. This also indicates good vibrational decoupling from using the heat pipe, and reduced water-induced vibration by up to 10x over certain frequency ranges.

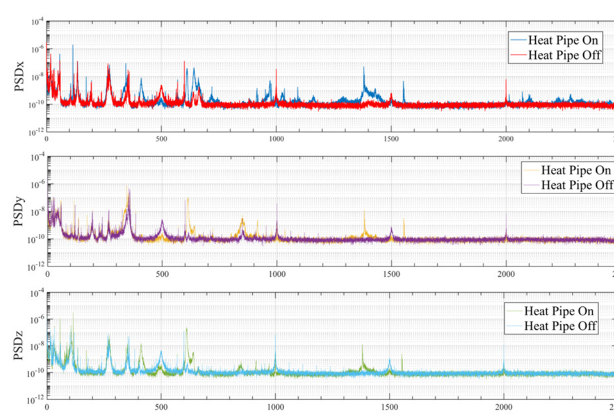

Figure 9: PSD with Heat Pipe Flow On/Off.

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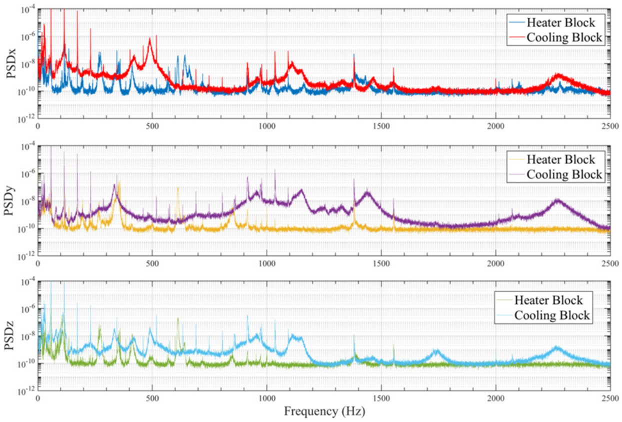

Figure 10: PSD for Hot and Cold Blocks with Flow On.

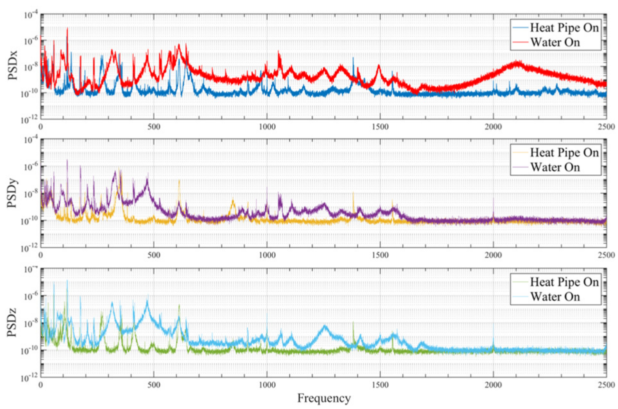

Figure 11: Vibrations - Heat Pipe vs. Direct Coupling with Flow On.

BEAMLINE APPLICATIONS

ALS Beamline 5.3.1 is a tender x-ray development beamline that uses an electromagnetically actuated laser shutter that has been modified for use in vacuum to act as a fast (<10 ms) shutter on the endstation. This modified design has been used in several other endstations at the ALS, and typically requires active water cooling of the mounting base to remove excess heat generated by the electromagnet. For this system, a COTS heat pipe was coupled to the magnet assembly to transport the waste heat to the side wall of the Aluminum vacuum chamber for thermal dissipation and subsequent air convection cooling.

Figure 12 shows the shutter assembly before installation, and Figure 13 shows the system installed in the vacuum vessel. The system has been shown to effectively cool the shutter assembly, with the contact area on the chamber wall being slightly warm to the touch. Exposure to vacuum and x-rays have not affected the heat pipe.

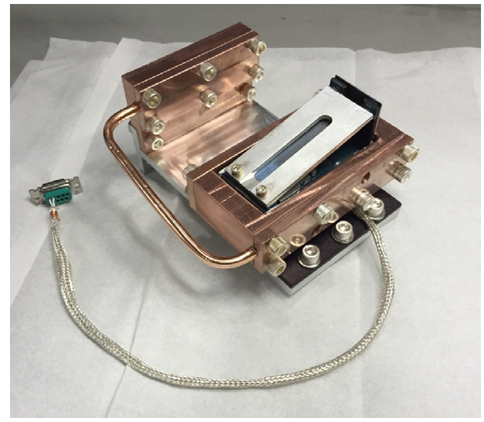
Figure 12: Shutter Assembly showing bent heat pipe conducting heat from shutter electromagnet to wall clamp support.

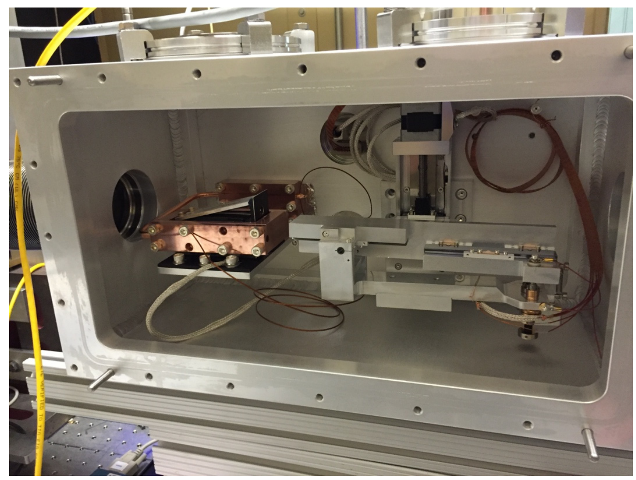
Figure 13: Chamber assembly showing shutter assembly (left of centre) clamped to the vacuum vessel.

CONCLUSION

Heat pipes, both custom and COTS can effectively be used to cool beamline components with minimal risk to UHV environments, and exposure to both vacuum and x-rays do not have deleterious effects on the system. They can also assist in reducing vibrations and offer simplified designs and reduced maintenance.

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