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Majorana Thermosyphon Prototype Experimental Setup

DJ Reid
AD Guzman
JT Munley

August 2011



Pacific Northwest
NATIONAL LABORATORY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Abstract

This report presents the experimental setup of Pacific Northwest National Laboratory's (PNNL's) MAJORANA DEMONSTRATOR thermosyphon prototype cooling system. A nitrogen thermosyphon prototype of such a system has been built and tested at PNNL. This document presents the experimental setup of the prototype that successfully demonstrated the heat transfer performance of the system.

Acronyms and Abbreviations

PNNL	Pacific Northwest National Laboratory
TC	thermocouple
psig	pounds per square inch gauge

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1.0 Experimental Design

Prior to building the thermosiphon setup, a three-dimensional SolidWorks¹ model was built (Figures 1.1 and 1.2)

1.1 System Overview

Figure 1.1 provides approximate dimensions in inches.

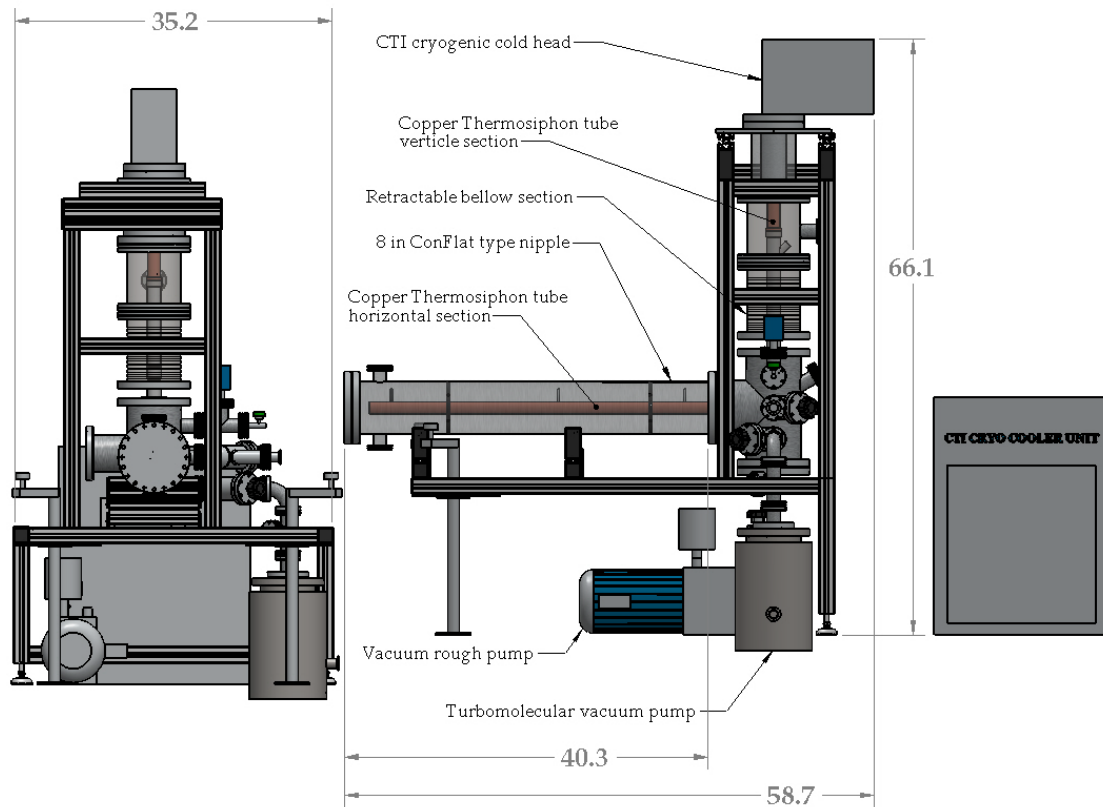


Figure 1.1. General Layout and Dimensions

This apparatus was assembled from a combination of commercial off-the-shelf components and custom fabricated hardware comprising four subsystems:

1. Cryogenic cooling and heat transport
2. Vacuum housing/pumping and thermal insulation
3. Physical support and positioning
4. Instrumentation

¹ Dassault Systèmes SolidWorks Corp.

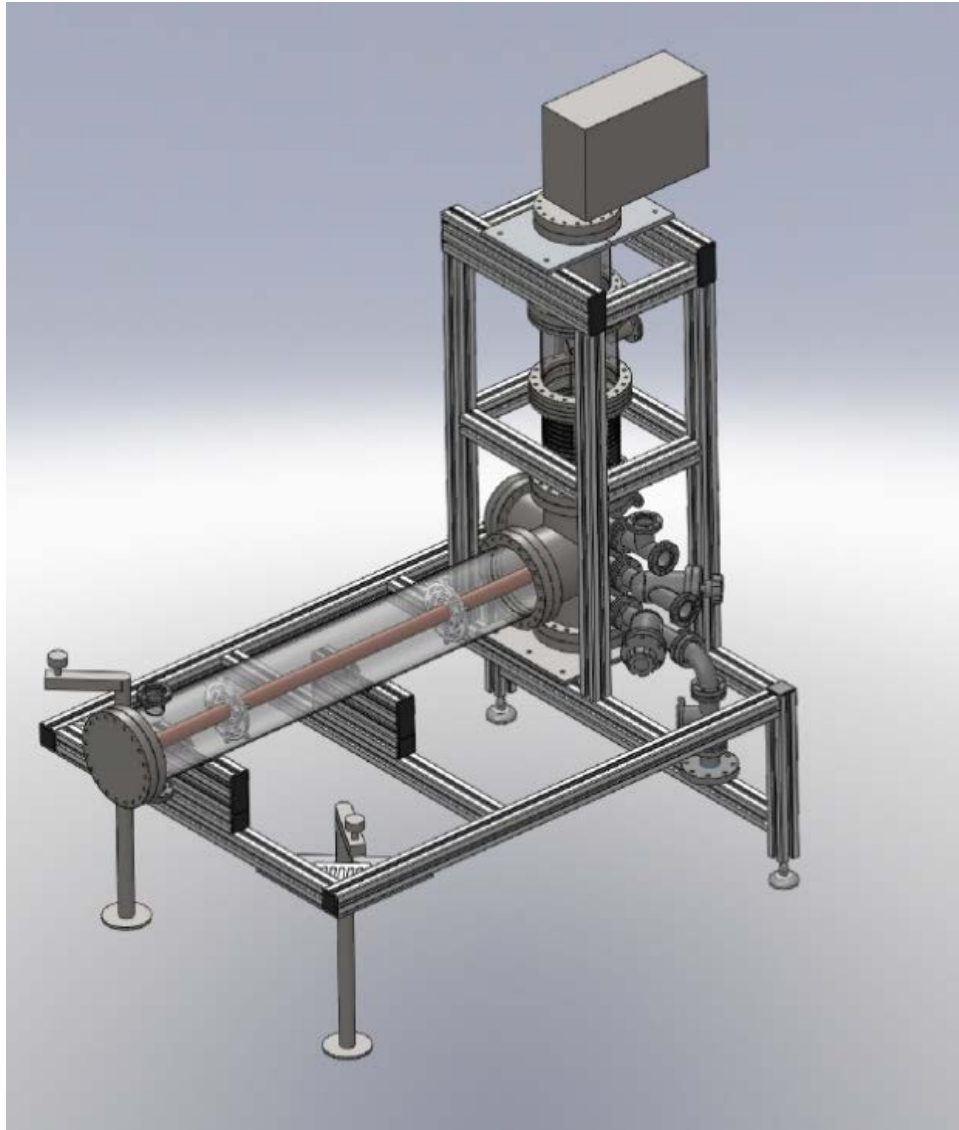


Figure 1.2. Illustration Showing the Horizontal Condenser Tube in the PNNL Thermosyphon

1.2 Cryogenic Cooling and Heat Transport

The thermosyphon has three main components: a condenser, an evaporator, and a vertical column that connects these two modules. The condenser for this experimental system is a mechanically cooled vertical copper rod acting as a cold finger. The mechanical cooler is a CTI-Cryogenics[®] helium refrigerator system² composed of a Model 8510 compressor and a cold head. The cold head is capable of extracting ~60 W at 80 K. The cooler is thermally coupled to the cold finger through a layer of indium. The evaporator is a horizontal copper pipe with a length matching that of the pipe going through the MAJORANA DEMONSTRATOR shield (see Figure 1.2). The experimental setup allows for the evaporator tube to be tilted in order to explore performance limits and the effect of a slight slope toward or away

² Helix Technology Corporation Model 1050 Cryodyne Refrigeration system. <http://helixtechnology.com>

from the evaporator tip where the primary heat load is applied. Figure 1.2 shows the computer-aided design model with the outer vacuum jacket shown transparent for clarity.

The heat transfer in the thermosyphon is carried out through evaporation and condensation of the two-phase nitrogen in the system. The thermosyphon tube volume is connected to an external pressurized nitrogen tank (ballast tank) with a volume much larger than that of the tube so that the system can be initially charged with a moderate nitrogen gas pressure at room temperature and sealed prior to cool down. The amount of nitrogen remains constant during operation. The total volume of nitrogen is equal to the internal volume of the evaporator tube plus the volume of the vertical column connected to the condenser plus the nitrogen gas ballast tank (approximately 40 liters). As the system is cooled and nitrogen gas condenses to liquid phase, the pressure in the system falls to near atmospheric pressure. Using a large volume ballast tank reduces the pressure requirements of the thermosyphon tube when all of the nitrogen is in the gaseous state, reducing the engineering and safety challenges of a highly pressurized system. The system operating pressure of 0 to 60 psig was monitored using a pressure gauge located on the line connecting the ballast tank to the thermosyphon body.

Figure 1.3 is the cryogenic pump used to cool the cold head of this apparatus.



Figure 1.3. CTI Cryogenic Pump

Figure 1.4 shows the rear panel of the cryogenic pump compressor. The braided lines transport the compressed helium to the pump unit shown in Figure 1.3.



Figure 1.4. Rear Panel of Cryogenic Pump Compressor

Figure 1.5 shows the thermal insulating PEEK³ piece used to support the copper tube inside the vacuum jacket.



Figure 1.5. PEEK Insulating Support

³ PEEK = polyether ether ketone

Figure 1.6 shows the cold surface of the cold head. The silver-colored material is a soft indium layer for thermal contact with the cold finger.

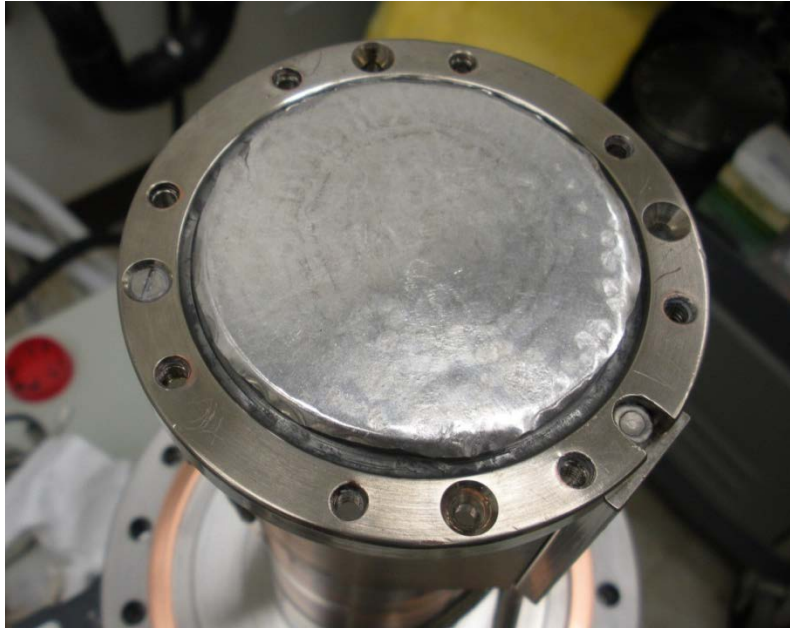


Figure 1.6. Cold Surface of Cold Head

Figure 1.7 shows the copper interface flange that connects the thermosyphon tube to the cold head of the CTI cryogenic unit.

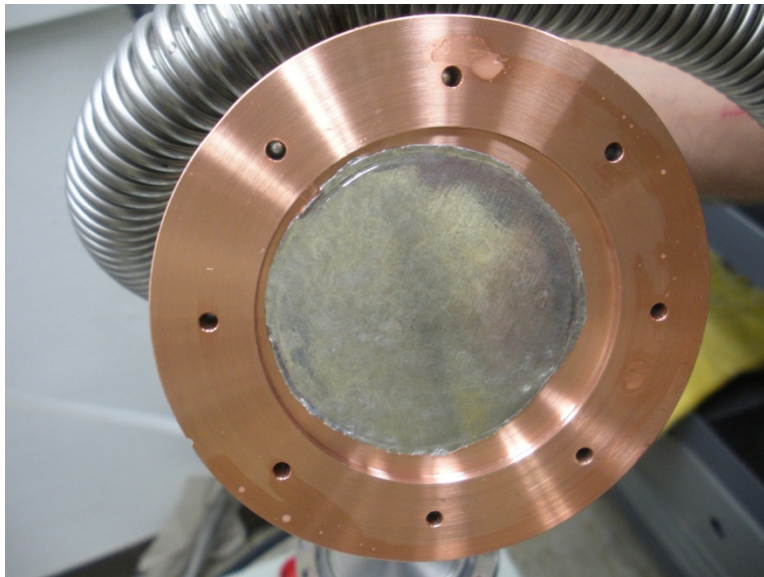


Figure 1.7. Interface Flange between Cold Finger and CTI Cryogenic Unit

1.3 Vacuum Housing/Pumping and Thermal Insulation

All vacuum components were of the copper gasket/knife edge style typically associated with the Conflat brand. Note that some of the vacuum components were fitted with Viton^{®4} gaskets rather than copper. Figure 1.8 shows the test setup in the laboratory.

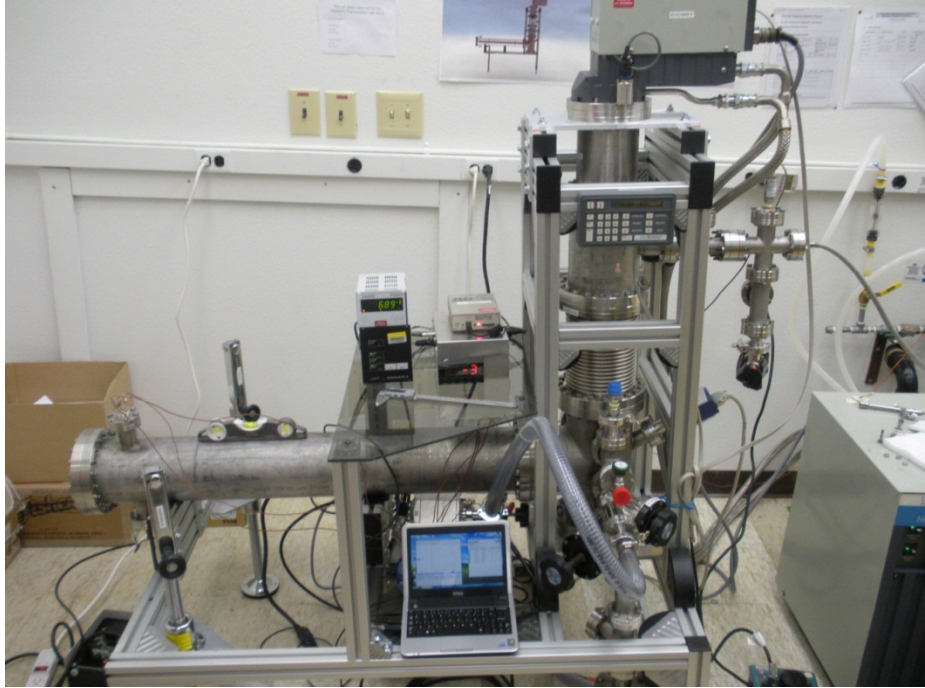


Figure 1.8. Complete Apparatus in Extruded-Aluminum Support Frame

Figure 1.9 shows the copper-to-stainless-steel transition used to couple the thermosyphon tube to the CTI Cryogenic pump.

⁴ Viton is a registered trademark of DuPont Performance Elastomers L.L.C.



Figure 1.9. Explosively Welded Copper-to-Stainless-Steel Transition

Figure 1.10 shows the underside of the thermosyphon tube bolted to the cold head. Note the coiled stainless steel bellows which supplied nitrogen from the ballast tank to the thermosyphon.



Figure 1.10. Cold-Head Interface Area with Nitrogen Supply Line

Figure 1.11 shows the nitrogen supply exiting the vacuum chamber via a bulkhead CF flange with a 1/2-in. VCR[®] fitting welded in its center.

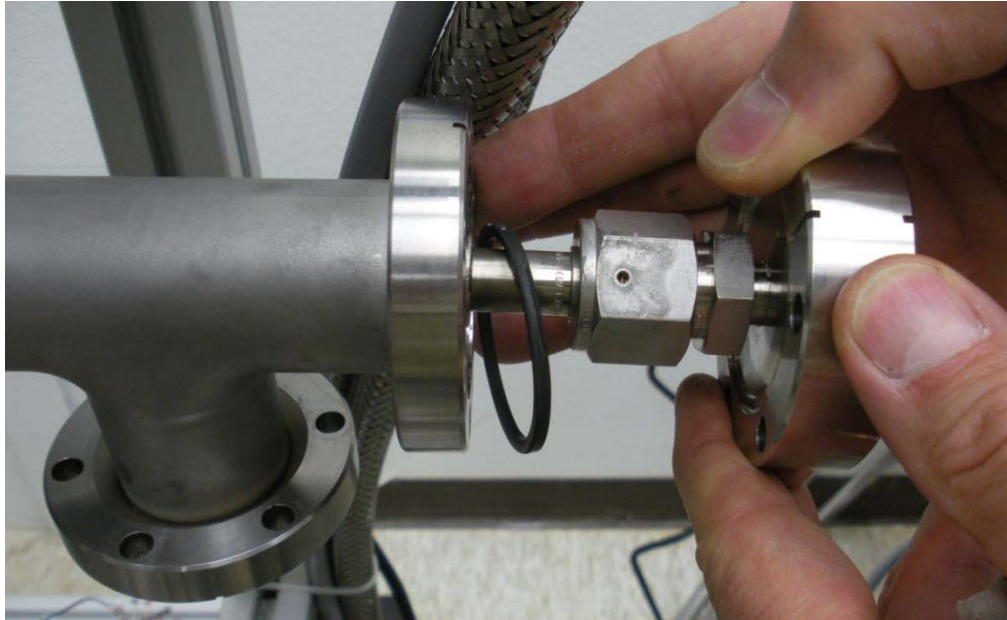


Figure 1.11. Nitrogen Supply to Bulkhead CF Flange

Figure 1.12 shows the apparatus with the large diameter stainless steel bellows retracted to allow access to the final thermosyphon connection. It was necessary to assemble the apparatus in two halves and then connect these two halves via the access provided by retracting the bellows; see Figure 1.1 for clarity.

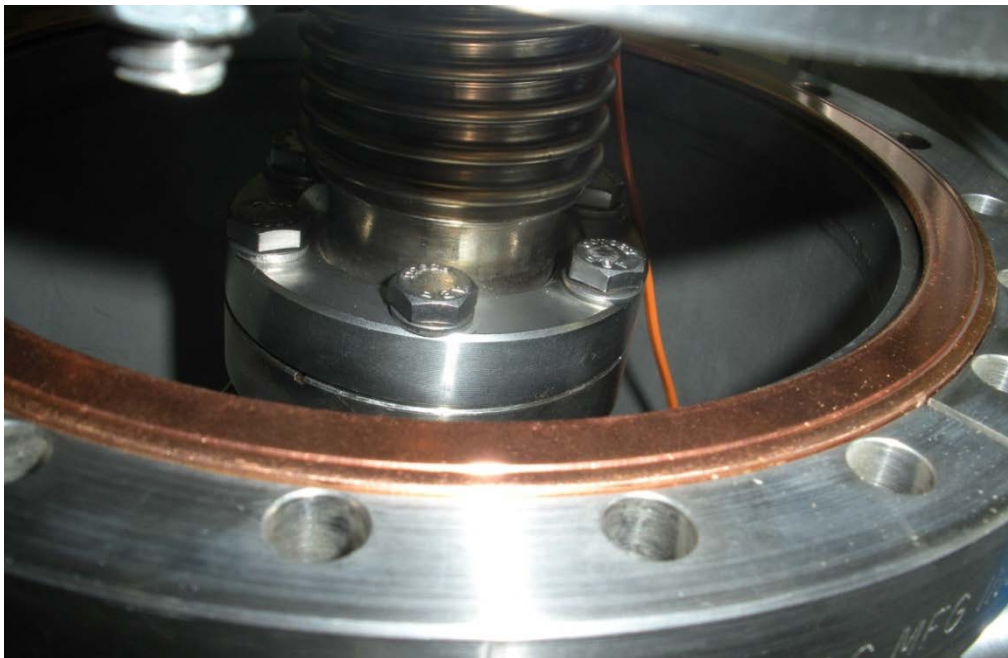


Figure 1.12. Thermosyphon Connection with Large Bellows Retracted for Final Assembly

Multiple layers of Mylar^{®5} film were wrapped around the thermosyphon tube to reflect black body radiation away from the vacuum housing, which was at room temperature; see Figure 1.13.



Figure 1.13. Mylar Reflective Film around Thermosyphon Tube

Figure 1.14 shows the Mylar installed around the nitrogen supply line bellows.

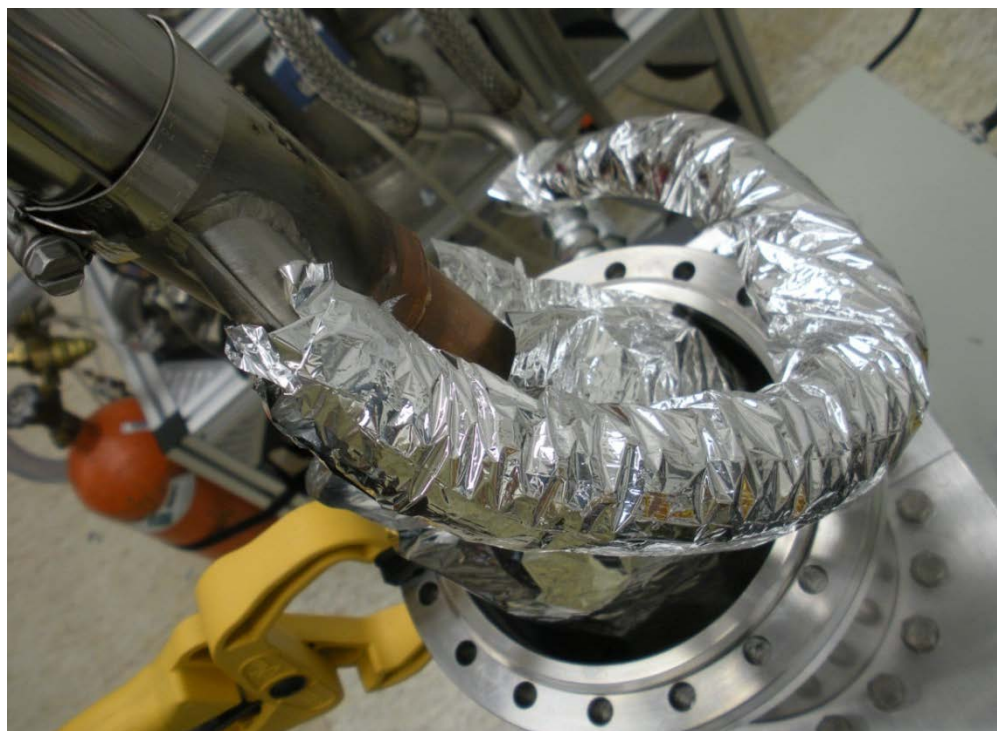


Figure 1.14. Mylar Film around Nitrogen Supply Line

⁵ Mylar is a registered trademark of DuPont Teijin Films.

Figure 1.15 shows the installation of Mylar prior to final closure.



Figure 1.15. Mylar Film at Final Vacuum Closure Point

Figure 1.16 shows the complete apparatus connected to a Leybold quadrupole mass spectrometer. The mass spectrometer was used in helium leak-test mode to test the vacuum integrity after final assembly.



Figure 1.16. Apparatus Connected to Leybold Quadrupole Mass Spectrometer

1.4 Physical Support and Positioning

The system was assembled from the middle outward, beginning by connecting the central vacuum chamber to the vacuum pump and conducting leak tests to verify vacuum tightness (see Figure 1.17). After this chamber was tested satisfactorily, each section was added and vacuum tested until the vacuum jacket was complete.

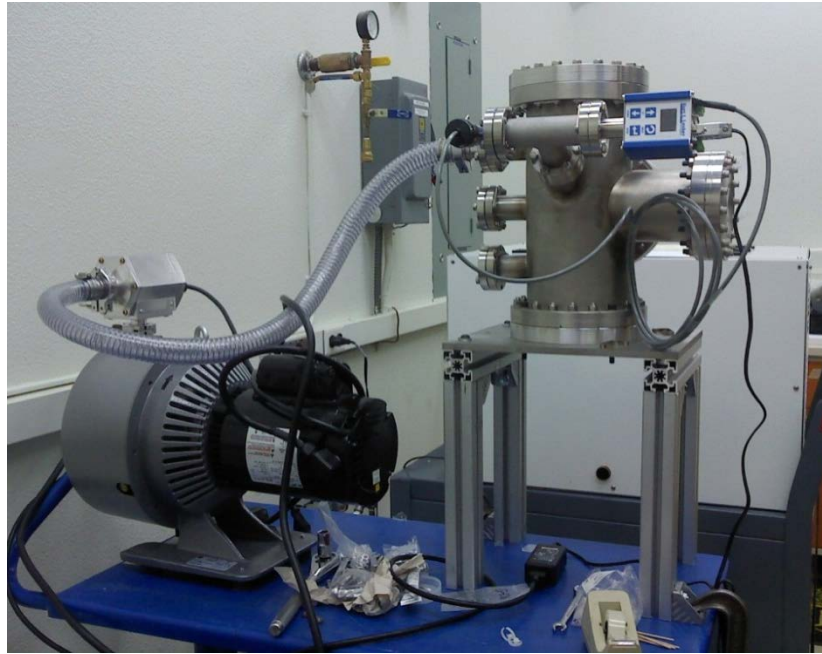


Figure 1.17. Apparatus Central Chamber Connected to Vacuum Pump

Figure 1.18 shows the level used to monitor the tilt of the experiment.



Figure 1.18. Magnetic Level Used to Monitor System Tilt

1.5 Instrumentation

The measure of success for the thermosyphon was its ability to transport heat from the heater at the far end of the copper tube to the cold head at the other end. Thermocouples mounted along the condenser tube were used to measure the temperature distribution as the liquid nitrogen made its way to the heated end and ultimately reached thermal equilibrium with the heat load. Thermocouple placement is shown in Figure 1.19. Thermocouple TC1 was located 4 inches away from the tip of the tube, TC2 was located 21 inches away from the tip, TC4 was located 36 inches away from the tip, and TC5 was located at the elbow leading to the condenser. Additional thermocouples were located within one of the PEEK supports for the evaporator tube (TC3) and at the condenser (TC6).

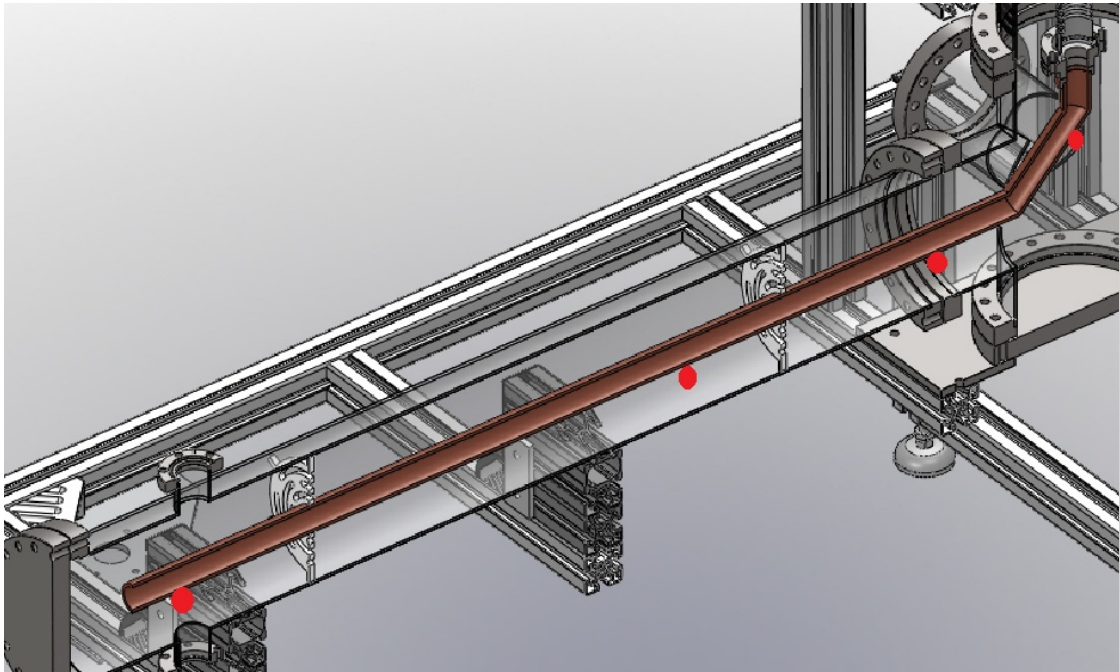


Figure 1.19. Placement of Thermocouples TC1 through TC4 from Left to Right along the Copper Evaporator Tube

Figure 1.20 shows one of the PEEK thermal insulators used to thermally isolate the copper tube from the outer vacuum housing. Also shown in Figure 1.20 is a stainless steel hose clamp holding one of the thermocouples in intimate contact with the copper tube.

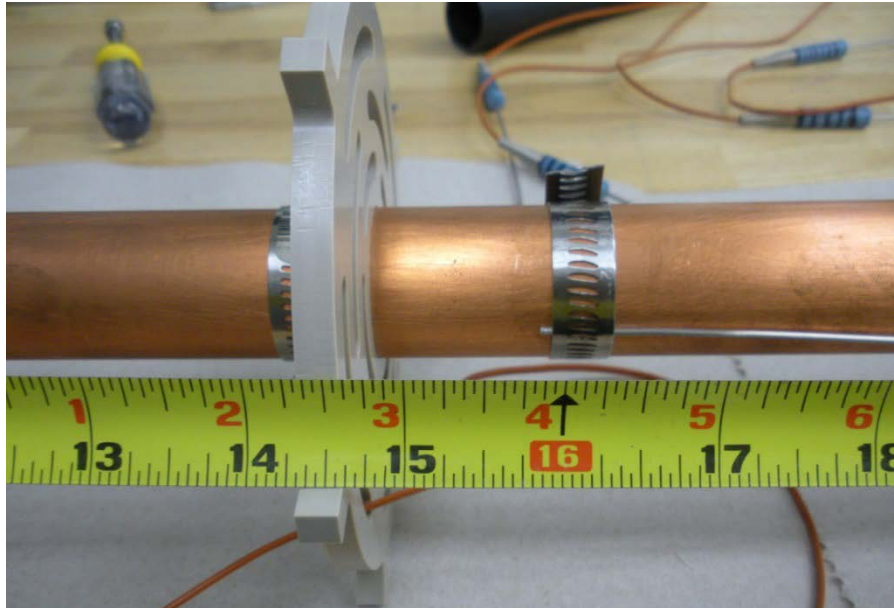


Figure 1.20. Insulating Support and Hose Clamp Mounting Thermocouple to Copper Tube

An adjustable electric heater (Figure 1.21) was placed at the tip of the tube to emulate the heat load created by the detector module. The adjustable heater at the tip of the evaporator tube was used to apply different heat loads within the range of interest, from 0 W to 25 W. The operating point of the two-phase nitrogen system was regulated by adjusting the cold-head temperature using a second heater embedded in the cold head.



Figure 1.21. Band Heater Clamped at the End of the Copper Evaporator Tube

Figure 1.22 shows the band heater power feedthrough.

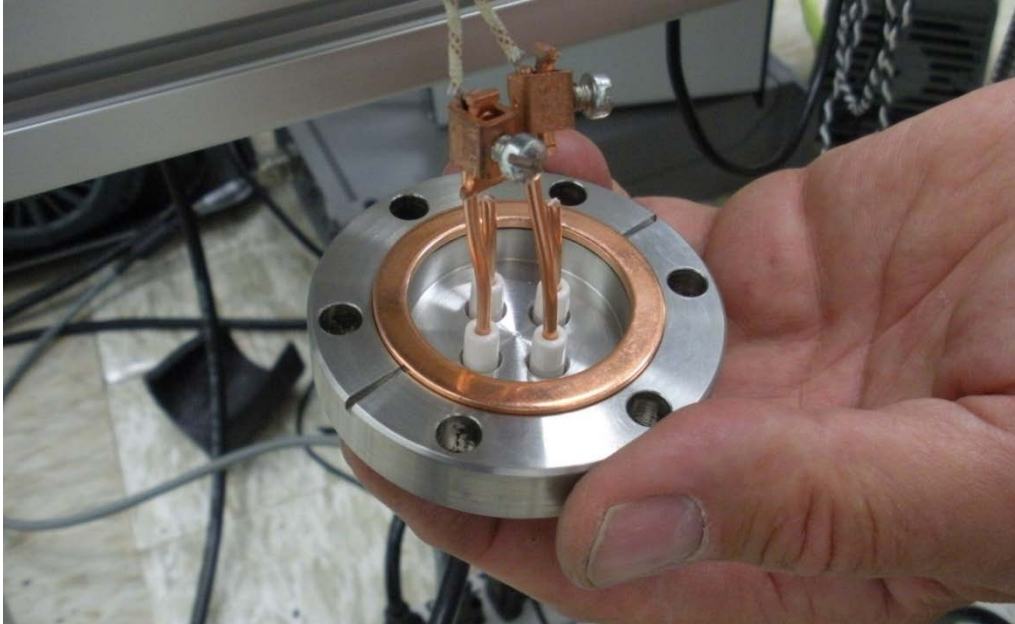


Figure 1.22. Heater Power Feedthrough

Figure 1.23 shows the thermocouple feedthrough.

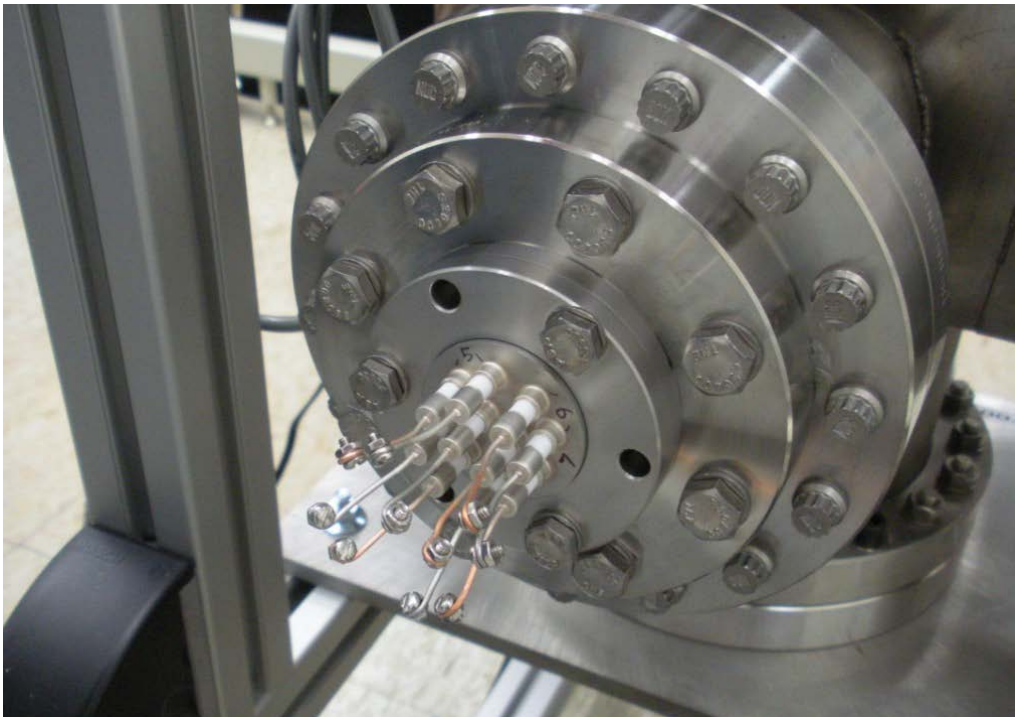


Figure 1.23. Thermocouple Feedthrough

2.0 Experimental Procedure and Results

The experimentation with the thermosyphon system started using 15 psig nitrogen pressure at room temperature. The amount of initial nitrogen charge was increased to 50 psig at standard temperature and pressure for the majority of the measurements presented. The operating pressure was kept in the range of 0 to 4 psig to represent the anticipated operating conditions when the cold head is replaced with an open liquid nitrogen reservoir to cool the condenser. The two-phase equilibrium was reached at different heat loads and the temperature and pressure were held stable during all experimental runs. The temperature gradient across the evaporator tube has been evaluated and characterized across the operating range of the thermosyphon; experimental results can be found in Fast et al. (2010).

3.0 Conclusions

With only minor design modifications, the thermosyphon experiment succeeded as a proof-of-principle experiment. The experiment showed excellent operation of the thermosyphon up to an applied 25 W heat load at the tip of the evaporator plus the thermosyphon base heat load of 9.4 W, even without a downward tilt of the evaporator tube toward the tip. Testing to higher heat loads to evaluate suitability for applications such as a ton-scale system will require a new condenser cooling system that eliminates the thermal interface between the thermosyphon condenser and the cold sink. The proposed design for the MAJORANA DEMONSTRATOR will address this critical design issue.

4.0 References

Fast JE, DJ Reid, and E Aguayo Navarrete. 2010. *Majorana Thermosyphon Prototype Experimental Results*. PNNL-20065, Pacific Northwest National Laboratory, Richland, Washington.

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