# A Powerful 10 K Pulse Tube Cryocooler with Cold Helium Circulation

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## ABSTRACT

A high capacity two-stage 10 K pulse tube cryocooler has been developed for remote cooling an $MgB_2$ superconducting magnet. The pulse tube cryocooler is equipped with a cold helium circulation circuit which uses around 8% of the compressor flow to circulate helium for remote cooling. The pulse tube cryocooler itself can provide 12 W at 10 K or 30 W at 20 K on the 2nd stage without a heat load on the 1st stage. It also has 10 W at 10 K on the 2nd stage with 60 W at 59 K on the 1st stage, simultaneously. For remote circulation cooling, this system can provide 4 W at <10 K for the object being remotely cooled and 60 W at 66 K on the 1st stage, simultaneously. The power consumption of the system is ~9.9 kW.

## INTRODUCTION

There are some requirements for remotely cooling objects at temperatures of 10-20 K, such as a cryogenic probe for NMR systems[1,2] and an $MgB_2$ HTS superconducting magnet[3]. M. Atrey, et. al. developed a cryoprobe cooled by a 10 K pulse tube cryocooler and demonstrated much less vibration than a GM cryocooler cooled cryoprobe[1].

Y. Iwasa at MIT proposed a method of cooling an $MgB_2$ superconducting magnet with solid nitrogen [3]. The $MgB_2$ magnet is immersed in solid nitrogen. The solid nitrogen is cooled by circulating cold helium gas in a copper cooling coil which is immersed in the solid nitrogen. This design will cool the superconducting magnets' entire surface area. It results in a very small temperature gradient along the magnet and a fast cool-down speed. Cryomech, Inc. was required by Francis Bitter magnet Laboratory (FBML), at MIT, to develop a 10 K cold helium circulation system for their new $MgB_2$ magnet. The cooling coil in the solid nitrogen is 6.35 mm OD and 15 m long. The cooling requirements are given below:

1. Average temperature of circulation helium is $\leq$10.0 K;
2. Cooling capacity on the cooling coil is 3.5 W at 10 K;
3. Temperature difference between the coil inlet and outlet is $\leq$ 1K.

A high capacity 10K pulse tube cryocooler has been developed and has been designated the model PT815 for this application. A cold helium circulation circuit is integrated on the PT815. This paper presents design and performance of this system.

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## SCHEMATIC AND SYSTEM DESIGN

Figure 1 shows the schematic of the PT815 two-stage pulse tube cryocooler with the cold helium circulation system and a cooling object. Two tee connectors (see figure 2) are installed on the high and low pressure lines to introduce a small portion of helium to the cold helium circulation circuit. There is a needle valve on the high pressure tee to control the flow rate. The cold helium circulation circuit includes the 1st and 2nd counter-flow heat exchangers (9,11), two heat exchangers (6,10) thermally attached to the 1st and 2nd stages, remote cooling lines (12) and a cooling objects (15). During testing, the cooling object (15) is a 6.35 mm OD and 12.7 m long copper coil. The manganin wire is wrapped around the center section of copper coil of ~1 m long.

Figure 2 shows the design of the PT815 with cold head circulation system. There are two VCR connectors at the ends of the 2nd heat exchanger and 2nd counter flow heat exchanger for connecting the remote cooling loop.

## EXPERIMENTAL RESULTS AND ANALYSIS

The PT815 cryocooler has been tested first without connecting the circulation loop. In the cryocooler performance test, the circulating heat exchangers are attached on the cold head. Figure 3 shows a map of cooling capacities of the PT815. The 1st stage performance was measured from bottom temperature to the temperature of < 75 K and the 2nd stage performance from the bottom temperature to ~20 K. It has 30 W at 20 K on the 2nd stage while the 1st stage has no heat load. It also provides 27 W at 20 K and 40 W at 51 K simultaneously on both stages. It is noticed that the increasing 2nd stage temperature in the range of below 10 K results in less performance of the 1st stage. However, the 1st stage performance will be slightly better if the 2nd stage temperature was continuously increased over 10 K.

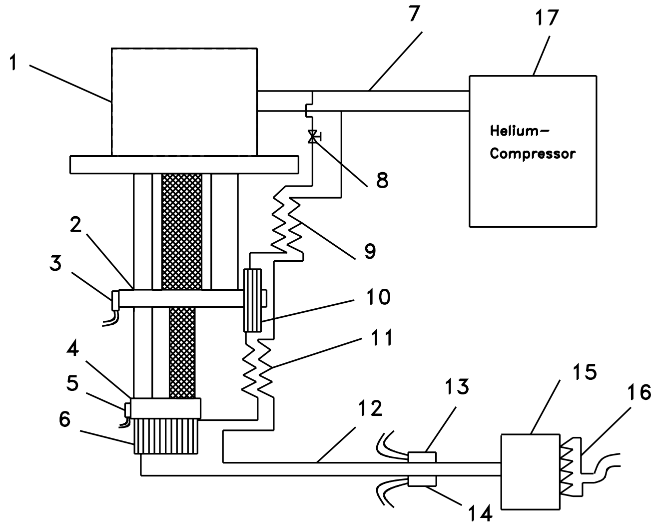

**Figure 1**. Schematic of the PT815 with the cold helium circulation. 1. PT815 cold head; 2. 1st stage cooling station; 3. temperature sensor; 4. 2nd stage cooling station; 5. temperature sensor; 6. 2nd heat exchanger; 7. flexible lines; 8. needle valve; 9. 1st counter flow heat exchanger; 10. 1st heat exchanger; 11. 2nd counter flow heat exchanger; 12. remote cooling lines; 13: temperature sensor at the outlet of the circulation loop; 14: temperature sensor at the inlet of the circulation loop; 15. cooling object (cooling coil); 16: heater; 17. Helium compressor.

**Figure 2**. Design of the PT815 with cold helium circulation heat exchangers

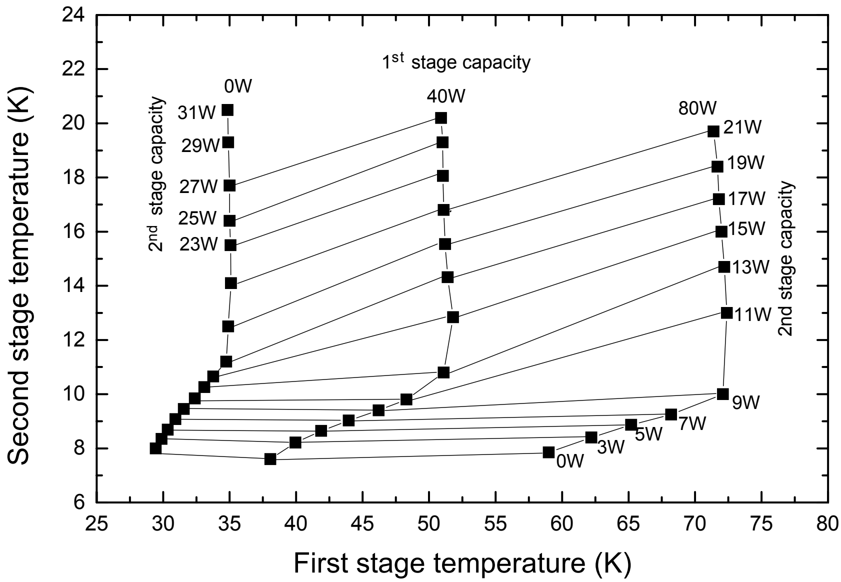

**Figure 3.** Cooling load map of the PT815

Table 1 gives the details of cooling capacity and power consumptions near 10 K. The 2nd stage can provide 11 W at 9.8 K with the 1st stage temperature below 50K. The 2nd stage capacity at 10 K begins to degrade if the 1st stage temperature is over 50 K. But it still can provide 7 W at 9.7 K with the 1st stage temperature of 81.2 K. The power consumption varies from 9.6 kW to 9.9 kW in all the tests near 10 K.

After testing the cryocooler performance, the cooling coil is installed in the circulation loop. The results below give the performance of the cold helium circulation system. The needle valve for controlling helium circulation flow opens with 5 turns in the following testing. Figure 4 shows the cool-down curve of the cooling coil and the 1st stage. It takes about 125 min for the cooling coil to reach the bottom temperatures of 7.64 K for the inlet and 7.70 K for the outlet. The 1st stage reaches a bottom temperature of 30.2 K in 150 min.

Figure 5 shows the circulation temperature at the inlet and outlet of the cooling coil with a heat load of 4 W. The vertical line in figure 5 indicates the cooling capacity on the 1st stage at the corresponding temperature. With the heat load of 4 W on the cooling coil, the temperature differences between the inlet and outlet is ~0.84 ± 0.01K in the current testing. It complies to the temperature difference requirement of ≤ 1 K with 3.5 W from FBML at MIT.

**Table 1.** Cryocooler performances near 10K

| | | | | | | |
|---|---|---|---|---|---|---|
| 1st stage capacity | 0 W at 32.4 K | 20 W at 38.3 K | 40 W at 48.3 K | 60 W at 58.8 K | 80 W at 72.0 K | 100 W at 81.2 K |
| 2nd stage capacity | 11 W at 9.84 K | 11 W at 9.81 K | 11 W at 9.80 K | 10 W At 9.81 K | 9 W at 10.0 K | 7 W at 9.7 K |
| Power consumption | 9.6 kW | 9.7 kW | 9.8 kW | 9.9 kW | 9.9 kW | 9.9 kW |

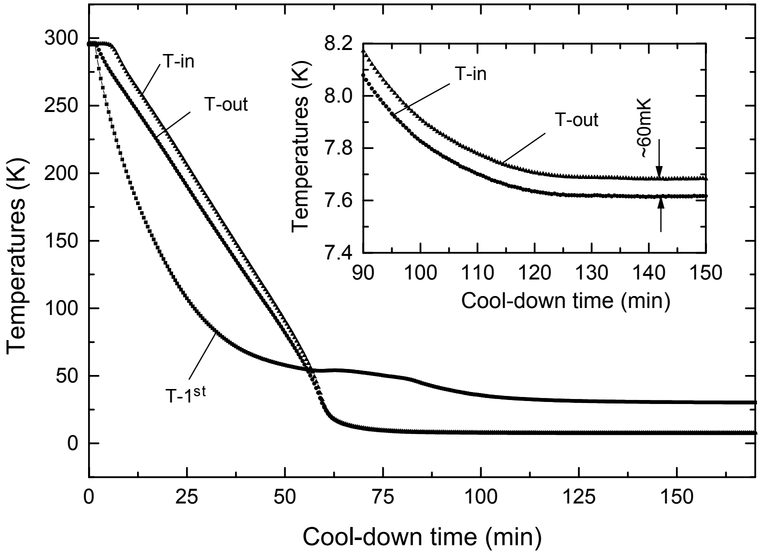

**Figure 4.** Cool-down curves of the PT815 with cold helium circulation. T-in: temperature at the inlet of the cooling coil; T-out: temperature at the outlet of the cooling coil; T-1st: temperature on the 1st stage.

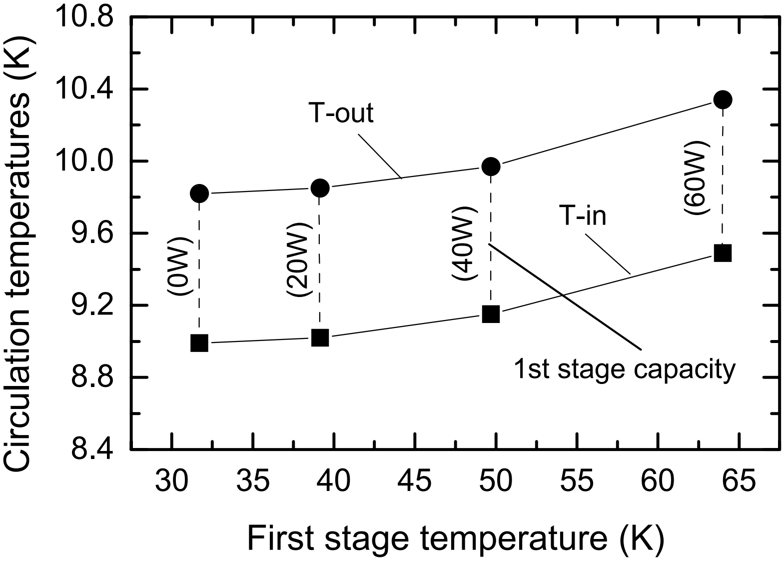

**Figure 5.** Circulating temperatures with 4 W heat load on the cooling coil. T-in: inlet temperature of the cooling coil; T-out: outlet temperature of the cooling coil.

Figure 6 shows the variations of the mass flow rate of the cold helium circulation with the different 1st stage temperatures. The mass flow rate varies from 0.51 g/s to 0.55 g/s when the 1st stage temperature increases from 32 K to 66 K, while the 2nd stage temperature is near 10K with the heat load of 4 W. The higher 1st stage temperature results in a higher pressure differential from the compressor and leads to higher the mass flow rate of the cold helium circulation.

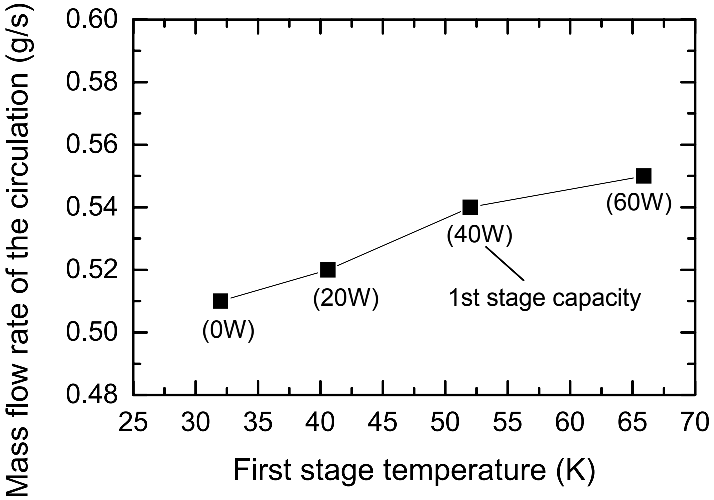

**Figure 6.** Flow rate of the cold helium circulation at different 1st stage temperatures.

## CONCLUSION

A 10K pulse tube cryocooler has been developed with cold helium circulation. The cryocooler compressor provides ~8% of its flow for circulating helium and the rest of the flow to the cryocooler. It can provide 4W of circulation cooling at temperatures below 10K. This device can be used for cooling cryoprobes for NMR systems, HTS superconducting magnets, and other applications in the future.

## ACKNOWLEDGMENT

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## REFERENCES

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