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To cite this article: AJ May *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **502** 012135

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Development of a sorption-cooled continuous miniature dilution refrigerator for 100 mK detector testing

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Abstract. As the forthcoming generation of Cosmic Microwave Background observatories move towards the use of large format detector arrays operating at ~ 100 mK, the need for test cryostats capable of operating in this temperature regime is becoming more pronounced. This has strongly driven the development of several related systems, including the continuous miniature dilution refrigerator (MDR) reported here. The MDR is comprised of a thermally separated mixing chamber, step heat exchangers, twin stills and twin condensation pumps. The pumps are alternately cooled to ~ 300 mK by a pair of single-shot ^3He sorption coolers (cycled in anti-phase) to circulate ^3He in the system. The system is therefore closed-cycle, with the circulation of ^3He , both in the MDR and sorption coolers, contained to the cold stage. As a result, the reliability of the system is improved through a mechanically simple design and the absence of external connections, gas handling systems, and cold o-rings.

1. Introduction

The forthcoming generation of Cosmic Microwave Background observatories will require the deployment large format arrays of background-limited detectors operating at 100 mK [1]. In order to meet the demanding production schedule for these arrays, there is a strong need for rapid feedback on the detector yield of individual wafers prior to undergoing detailed testing and characterisation. This has driven the development of a fast cooldown test cryostat.

To cool below 100 mK, the typical approach is the use of either adiabatic demagnetisation refrigeration (ADR) or dilution refrigeration (DR) [2]. However, due to the sensitivity of these types of detectors and their readouts to magnetic fields, ADR use is made challenging by the shielding requirements. Furthermore, conventional DRs may be prohibitively expensive (largely due to the required amount of ^3He) as well as providing superfluously high cooling powers.

An alternative approach is the development of a test cryostat using a miniature dilution refrigerator (MDR) which requires far less ^3He than a conventional diluter by confining the circulation to the cold stage. A design has been developed for such a system that is capable of meeting the cooling power requirements for preliminary detector wafer testing at 100 mK.

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2. Cryostat architecture

A dry cryostat architecture is used. In the testbed cryostat for the MDR, a Gifford-McMahon (GM) cryocooler is used, providing a first stage at ~ 40 K and a second stage at ~ 4 K, both for radiation shielding and heat sinking of wiring and other mechanical connections. The model used, a Sumitomo RDK-415D³, provides a nominal cooling power of 1.5 W at 4.2 K.

A pair of ^3He sorption coolers are mounted to the 4 K stage of the GM and provide two 300 mK stages which may be operated independently. These stages are used firstly to precool the MDR and then to operate the condensation pumps to circulate the ^3He within the MDR. The still of the MDR operates at 700 mK and the mixing chamber <100 mK to cool the detector wafers under test. The sorption coolers and MDR are described in Sections 3 and 4 respectively.

The test cryostat is proposed to operate in a “push button” mode to 100 mK; cycling of the precooling stages is automated by an XML script controlling the various heaters in the system. As such, a wafer may be mounted in the test cryostat, the system closed and evacuated, and the cryocooler and scripts run overnight to reach 100 mK for testing the following morning.

3. ^3He sorption coolers

A pair of single-shot ^3He sorption coolers are mounted from the second GM stage, as shown in Figure 1. As shown in Figure 2, the coolers each comprise a cryopump, a single pumping line down to a condenser block, a pair of parallel pumping lines and an evaporator pot.

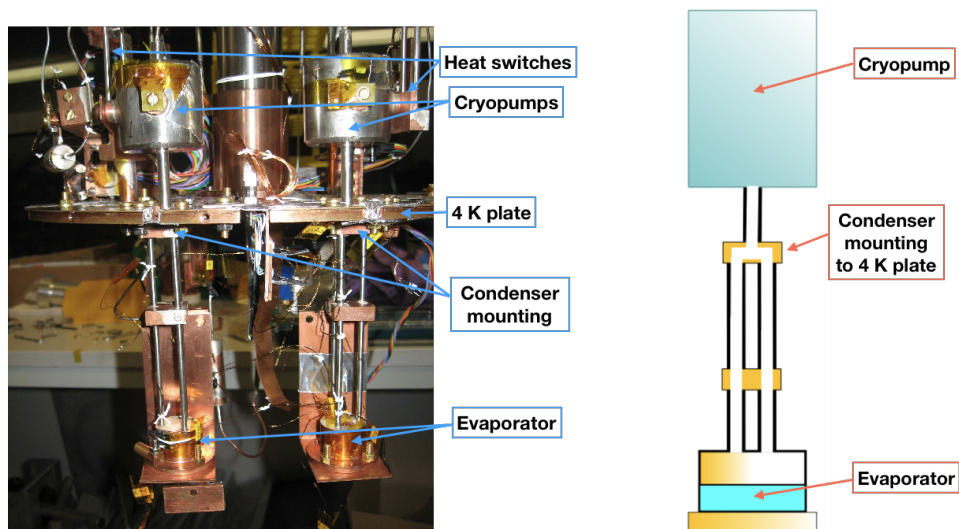


Figure 1. Dual fridges mounted in dewar **Figure 2.** Schematic of a single ^3He cooler

The cryopump chamber is packed with charcoal pellets. At ~ 4 K, the charcoal strongly adsorbs the helium gas, acting as a very effective pump. When heated to ~ 40 K the charcoal will strongly desorb almost all of the helium [2]. The temperature of the cryopump is controlled by means of an active convective heat switch (linking the pump to the 4 K stage) and a heater. The pump is cooled by closing the switch to couple to the 4 K stage. The pump is warmed by opening the switch and applying a voltage across a small resistor, acting as a heating element.

The cooler shown on the left of Figure 1 is referred to as 3He1 and the cooler on the right 3He2; respective components are also named accordingly, i.e. the evaporator of 3He1 is EV1, the heat switch is HS1, and so forth.

³ www.shicryogenics.com

The coolers are single-shot and cycled as follows:

- (i) The temperature of the cryopump is raised to desorb the helium gas; the gas liquefies in the condenser (coupled directly to the GM second stage) and collects in the evaporator
- (ii) The cryopump is then cooled to pump on the liquid in the evaporator; the evaporator cools until the pumping rate is equal to the boil-off rate (~ 350 mK)
- (iii) After some length of time determined by the amount of liquid condensed and the applied heat load, the liquid is exhausted, the evaporator will begin to warm, and the cooler must be recycled by returning to the first step

The duty cycle is the proportion of the above process during which the cold head is at its base temperature; this is typically in the region of 90%. This efficiency of duty cycle is therefore more than sufficient under typical loading to cycle the coolers in anti-phase such that at least one of the evaporators is always at 300 mK. The temperatures of the two evaporators during cycling is shown in Figure 3. The deviation from 300 mK is due firstly to the expiration of the liquid in the cold head, and subsequently the entry of warm gas and liquid into the evaporator when the cryopump is recycled and the liquid begins to cool.

It should be noted that in this architecture, the temperature of the second GM stage is sufficient to condense ^3He without the need for a ^4He precooling stage (for an example, see [3]). Furthermore, the design of these coolers is simplified significantly compared to that of ^4He coolers as there is no need for a superfluid film breaker to confine the liquid to the evaporator pot. The measured load curves for these coolers are shown in Figure 4.

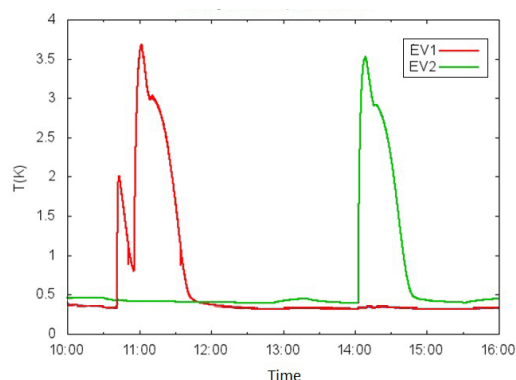


Figure 3. EV temperatures during recycling

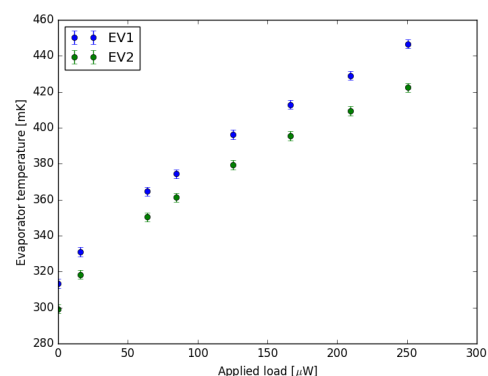


Figure 4. Measured load curves

4. Miniature dilution refrigerator

An MDR stage is mounted from the dual ^3He evaporators in order to provide cooling < 100 mK for the detector test stage. Several MDR architectures have previously been reported [3, 4, 5, 6, 7, 8, 9]; these variously use differing complexities of precooling architectures and either a sorption pump (necessarily single shot) or condensation pump (continuous) to drive the circulation of ^3He through the system. As such, MDRs confine the ^3He to the cold stage and therefore do not require any external gas connections and no room-temperature gas handling system as for conventional dilution refrigerators. They are therefore well-suited to small-scale fast cooldown to 100 mK. A prototype cooler has been manufactured as shown in Figure 5, with an illustrative schematic shown in Figure 6.

Both stills are operated at ~ 700 mK and may each be pumped on by one of the pair of condensation pumps. The condensation pumps are each mounted to one of the ^3He evaporators;

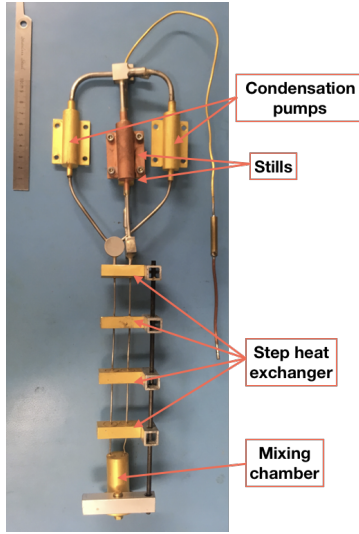


Figure 5. MDR prototype. The second still is obscured by the first. The total height of the unit is 32 cm.

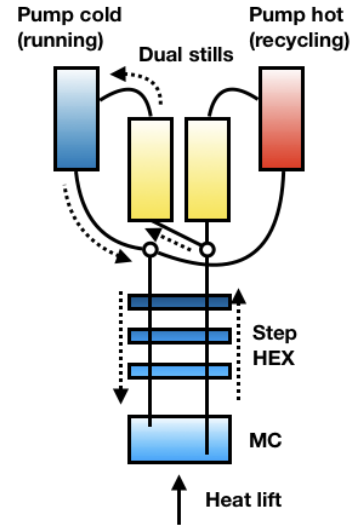


Figure 6. MDR schematic

the ^3He systems are recycled in antiphase such that at least one pump is cold at all times. Dual stills are used to prevent convection between the two condensation pumps when recycling one side; without the liquid trap, warm gas from the condensation pump being recycled can load the cold pump, preventing it from reaching the required base temperature. Furthermore, a superfluid film breaker at the top of each still prevents the development of a film along the pumping line as a result of the thermomechanical effect when the pumps are recycled [3].

The condensation pumps themselves are simply small cylindrical chambers with conical internal lower profiles to prevent trapping of the liquid. When the chamber is cooled to ~ 300 mK, the differential vapour pressure drives the flow of ^3He from the still. The gas then condenses in the pump and flows under the action of gravity through a series of step heat exchangers to the mixing chamber at ~ 100 mK.

The return line from the mixing chamber passes back through the step heat exchangers before branching off to the two stills; ^3He is driven along this line by an osmotic pressure gradient as in a conventional dilution refrigerator. As ^3He is continuously circulated from at least one of the stills as described, constant cooling at ~ 100 mK is provided for the detector wafer under test.

In order to support preliminary detector testing, the MDR is required to provide a heat lift of $\sim 5 \mu\text{W}$ for >8 hours. As constant cooling is provided, the hold time is not a limiting factor for the design; this also greatly increases the scope for other small-scale 100 mK applications which require longer hold times. The cooling power of dilution is given by the first law of thermodynamics as the difference in rate of enthalpy leaving and entering the chamber. In this temperature regime, the molar enthalpy of the incoming pure ^3He and of the dilute solution approximate to $12T^2$ and $94T^2$ J/mol respectively [10], hence the cooling power \dot{Q}_{MDR} is

$$\dot{Q}_{MDR} = \dot{n} (94T_m^2 - 12T_i^2) \quad (1)$$

where \dot{n} is the molar flow rate of ^3He , T_m is the temperature of the mixing chamber and T_i is the temperature of the returning ^3He . If a perfect heat exchanger is assumed, then $T_i = T_m$ and the maximum heat lift is achieved of

$$\dot{Q}_{MDR} = 82\dot{n}T_m^2 \quad (2)$$

Clearly, perfect heat exchanger performance will not be achieved in reality. As such, a safety factor was considered in the prototype design, with the view that several iterations of the heat exchanger may be required. In this version, a step heat exchanger design is used, with the chambers in the exchanger blocks packed with copper braid to increase the effective surface area and reduce Kapitza resistance. The performance of the heat exchanger will be determined experimentally, and it is considered that it may be required to use a more efficient design for the higher temperature section such as a tube-in-tube design.

The ^3He flow rate is determined firstly by the rate of pumping from a single still to a condensation pump. As such, the flow rate is controlled by setting the still temperature up to a limit set by the capacity of the pumps.

The heat load on one of the condensation pumps (and hence the ^3He cold head) $\dot{Q}_{3\text{He}}$ is

$$\dot{Q}_{3\text{He}} = \dot{n}\Delta H \quad (3)$$

where ΔH is the difference in enthalpy leaving and entering the pump. Here, the latent heat of vapourisation L dominates and hence the flow rate is

$$\dot{n} \sim \frac{\dot{Q}_{3\text{He}}}{L} \quad (4)$$

The measured load curves in Figure 4 show that the system will comfortably support a flow rate suitable to provide a heat lift at the mixing chamber of up to 10 μW at 100 mK.

5. Conclusion

The development has been reported of a miniature dilution refrigerator and precooling ^3He sorption coolers which exceed the requirements for a test cryostat to provide rapid cooldown and support preliminary testing of detectors operating at 100 mK. The design, operation, and a preliminary thermodynamic analysis have been provided.

The sorption coolers have been operated extensively and their performances reported. A prototype MDR has been manufactured and is currently awaiting testing; the authors look forward to reporting full experimental results in due course.

Acknowledgments

The authors would like to thank the School of Physics and Astronomy Machine Shop at the University of Manchester for their exceptionally skilled machining of many of the parts described in this paper. This work was supported by STFC grant ST/L000768/1. AJM is supported by an STFC PhD studentship.

References

- [1] Abitbol M H, Ahmed Z, Barron D, Thakur R B, Bender A N, Benson B A, Bischoff C A, Bryan S A, Carlstrom J E, Chang C L *et al.* 2017 *arXiv preprint arXiv:1706.02464*
- [2] Pobell F 1996 *Matter and methods at low temperatures* vol 2 (Springer)
- [3] May A J *et al.* 2016 Sorption-cooled continuous miniature dilution refrigeration for astrophysical applications *Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II* vol 9912 (International Society for Optics and Photonics) p 991266
- [4] Teleberg G, Chase S and Piccirillo L 2008 *Journal of Low Temperature Physics* **151** 669–674
- [5] Prouvé T, Luchier N and Duband L 2008 Pocket dilution cooler *submitted for publication in the proceedings of the 15th International Cryocooler Conference, Long Beach, CA*
- [6] Melhuish S J, Martinis L and Piccirillo L 2013 *Cryogenics* **55** 63–67
- [7] Brien T, Castillo-Dominguez E, Chase S and Doyle S 2018 *arXiv preprint arXiv:1801.07442*
- [8] Edel'man V 1972 *Cryogenics* **12** 385–387
- [9] Sivokon V, Dotsenko V, Pogorelov L and Sobolev V 1992 *Cryogenics* **32** 207–210
- [10] Radebaugh R 1967 *NBS Technical Note* **392**