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# A continuous dry 300 mK cooler for THz sensing applications

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We describe and demonstrate the automated operation of a novel cryostat design that is capable of maintaining an unloaded base temperature of less than 300 mK continuously, without the need to recycle the gases within the final cold head, as is the case for conventional single shot sorption pumped $^3$He cooling systems. This closed dry system uses only 5 l of $^3$He gas, making this an economical alternative to traditional systems where a long hold time is required. During testing, a temperature of 365 mK was maintained with a constant 20 $\mu$W load, simulating the cooling requirement of a far infrared camera.  [http://dx.doi.org/10.1063/1.4945691]

## I. INTRODUCTION

Cooling apparatus to sub-Kelvin temperatures is now a standard practice in many research laboratories around the world, including locations as diverse as mountaintop astronomical observatories[1] and deep underground laboratories.[2]

The availability of mechanical coolers[3] has made such systems much easier to operate by removing the need to repeatedly refill a cryostat with liquid helium. Transferring liquid helium is time-consuming and potentially dangerous. Moreover, helium is expensive and obtaining a sufficient supply is not always easy. Mechanical coolers need only an electrical supply to operate and no particularly specialised skill is required from the operator. Therefore they also enable the use of cryogenics in applications outside the research laboratory where handling liquid helium can be completely impractical.

An example of this is the detection of Terahertz radiation where cryogenic passive detectors can provide high sensitivity over a wide spectral range, with no need for a source of Terahertz illumination. Applications for these detectors include spectroscopy,[4] fusion diagnostics,[5] atmospheric science,[6] and security screening.[7]

However, whilst temperatures of 3-4 K are sufficient for many applications, the highest detector sensitivities are only achievable at temperatures below 1 K. Commercially available mechanical coolers can only reach temperatures of—at best—a few Kelvin, and further cooling methods are necessary to attain lower temperatures. The most common method is to pump on a liquid $^3$He bath to reduce the vapour pressure whereby temperatures of 300 mK and below can be reached. To get continuous cooling, these systems use external pumps to circulate the $^3$He gas and hence require a gas handling system and sealed pumps outside the cryostat with the risk of losing expensive $^3$He due to equipment failure or user error.[8]

An alternative system, albeit with lower cooling power, is to use a completely self-contained refrigerator using internal sorption pumps.[9] Such systems are simple to use, can be completely automated, and have little risk of user error causing the loss of $^3$He. Furthermore, the small internal volumes compared with an externally pumped system minimise the quantity of $^3$He required.

However, unlike an externally pumped system, the sorb pumped systems do not provide continuous cooling—once the charge of $^3$He has been exhausted, the cooling terminates whilst the $^3$He is re-liquefied (referred to as cycling the fridge). The period during which the fridge is at the required temperature varies from a few hours to days, depending on the cooling power required and the quantity of $^3$He in the system. Additionally, $^3$He is extremely expensive (~$2500 per STP litre of gas) and often difficult to obtain. Hence there is a desire to minimise the quantity of $^3$He which in turn limits the cold hold time.

An obvious solution to obtain a continuous cooling with limited $^3$He is to operate two fridges in parallel. Each fridge then only needs to have sufficient $^3$He to stay cold whilst the other fridge is cycling. This solution results in a system with minimal $^3$He gas and indefinite hold time. However, the difficulty in designing such a system resides in the ability to provide good thermal contact to the fridge which is operating whilst having sufficiently good thermal isolation from the fridge which is being cycled. Here we report on a novel solution which utilises two $^3$He sorption fridges with a third cold head which is cooled by circulating $^3$He gas between heat exchangers on the sorption fridges. The success of this design lies in the stage of operation during which one of the heat exchangers is warm, and the other is cold.

As well as being able to provide indefinite cooling at temperatures ~300 mK for THz detection and other applications, our system could provide pre-cooling for a miniature dilution refrigerator[10] providing continuous cooling to temperatures below 100 mK. Such temperatures are required for the highest sensitivity THz detectors[1,7] and various other applications including fusion diagnostics,[5] atmospheric science,[6] and security screening.[7]

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## II. SYSTEM OVERVIEW

A schematic diagram of the complete system is shown in Fig. 1. The system comprises a pulse tube cooler, two $^4$He/$^3$He sorption refrigerators (labelled system A and system B operated in a cyclic fashion), and a third closed $^3$He unit that is continuously cooled by one of the two $^4$He/$^3$He sorption refrigerators. Each part of the system will be discussed below.

### A. Mechanical architecture and the pulse tube cooler

The cryostat is built around a commercially available two-stage PT405 Pulse-Tube Cooler (PTC) purchased from Cryomech,[11] which provides 22 W of cooling power at 65 K, 0.45 W of cooling power at 4.2 K, and has an unloaded base temperature of 2.8 K. The PTC is a self-contained liquid cryogen free unit that must be housed within a high vacuum enclosure. To this end, the PTC is held within an Outer Vacuum Can (OVC) lined with aluminium foil to reduce radiative power loading. The OVC is 811 mm in height and has a diameter of 300 mm. The entire enclosure, shown in Fig. 2, is supported within a frame that allows the system to be rotated easily by a single person such that the cryogenic cold stage is accessible without additional mechanical lifting equipment.

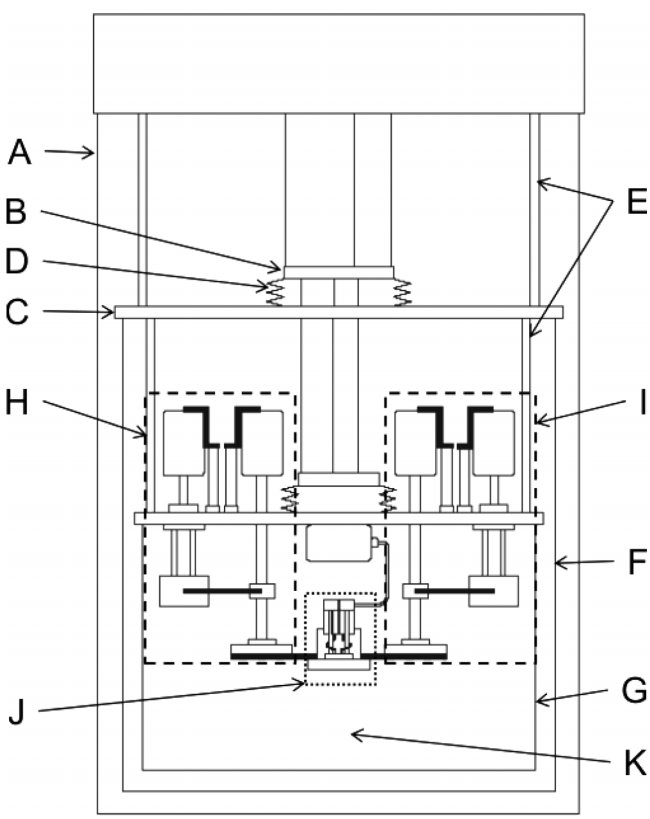


FIG. 1. The system is enclosed within an Outer Vacuum Can (OVC) (A). The Pulse Tube Cooler (PTC) (B) is thermally linked to the cold plates (60 K plate shown by (C)) by several thin copper foils (D). Each cold plate is mechanically supported by hollow stainless steel tubes (E), and each stage is enclosed within a Multi-Layer Insulation (MLI) covered thermal shield (60 K shown by (F), 4 K shown by (G)). The precooler units ((H) and (I), dashed boxes) continuously cool the final $^3$He pot ((J), dotted box). The experimental working space would be located at (K). The thick solid black lines indicate thermal links.

Gold-plated copper plates are thermally linked to each of the temperature stages (referred to as the 60 K- and 4 K-stages) of the PTC via multiple copper foils designed to provide vibrational isolation. Additionally, each plate is mechanically supported by four thin-walled low thermal conductivity stainless steel legs. An estimated 1 W of power is conducted down these legs from room temperature to 60 K, and 70 mW from 60 K to 4 K. These plates also form the top of Multi-Layer Insulation (MLI) covered copper 60 K and 4 K radiation shields with diameters of 241 mm and 203 mm, respectively. We estimate a radiative heat load on the 60 K shield of ~2 W from the OVC, and 1 mW on the 4 K shield from the 60 K temperature stage. The 4 K plate mechanically supports the two $^4$He/$^3$He sorption refrigerators and provides the condensation point for the gas within the $^4$He units, which has a critical temperature of 5.2 K. Since the actual condensation temperature significantly affects the overall amount of gas that is liquefied, it is important to reduce thermal loading on each stage through careful choice of materials to achieve the lowest temperature possible. In this system, we achieve a condensation temperature of 3.6 K on the 4 K plate.

### B. Precooler units: $^4$He/$^3$He sorption refrigerators

The schematic diagram in Fig. 1 shows a closed $^3$He unit that is continuously cooled by one of the two $^4$He/$^3$He sorption refrigerators. All of the closed cryogenic units in this system were designed and manufactured by Chase Research Cryogenics Ltd.;[12] a labelled photograph of the low temperature stages is shown in Fig. 3 and a schematic diagram of the these

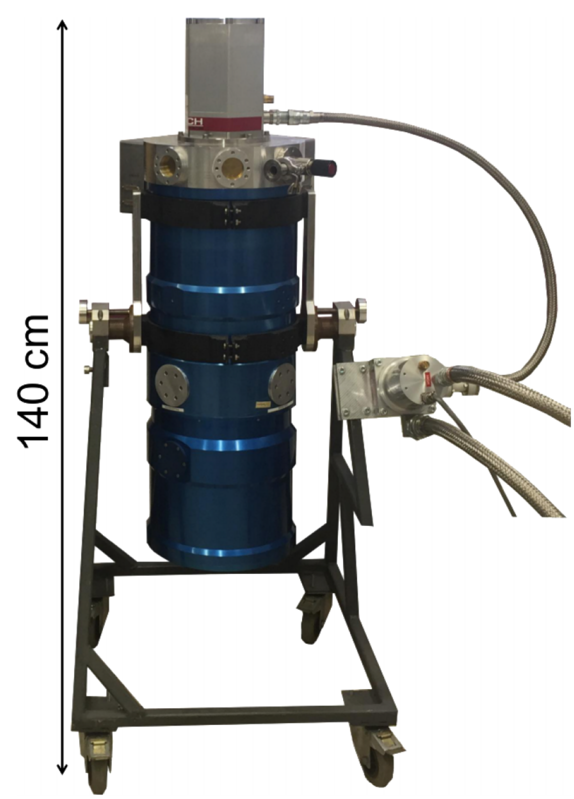


FIG. 2. Photograph of the full system and the supporting frame. The PTC remote motor is clamped to the frame, as shown on the right of the photograph.

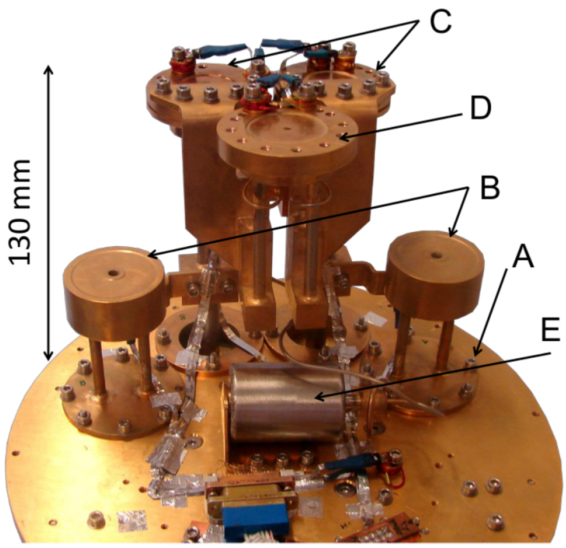


FIG. 3. Photograph of the underside of the continuous 300 mK cooler system as viewed from below. The $^4$He/$^3$He sorption pumps are supported by the 4 K plate (A) with a diameter of 227 mm. The two $^4$He cold heads (B) are used as condensation points for the two $^3$He precoolers (C), which operate cyclically to continually cool the final $^3$He head (D). An expansion tank (E) is mounted on the 4 K plate to allow for the room temperature $^3$He gas volume.

stages is shown in Fig. 4. An overview of a single $^4$He/$^3$He sorption refrigerator will be provided here before describing the continuously cooled unit in more detail.

Generally, a sorption refrigerator is a completely sealed vessel filled with either $^4$He or $^3$He gas.[12] The closed vessel is comprised of a sorption pump (in this case the adsorbent material is activated charcoal) connected to a cold pot where liquid cryogens can collect via tubes of low thermal conductivity (in this case thin walled stainless steel). A condensation point for the gas is provided by either the 4 K plate for $^4$He gas or the pre-cooled $^4$He cold pot for $^3$He, which has a critical temperature of 3.3 K. Each sorption pump in this design is connected to the 4 K plate via a $^4$He gas-gap heat switch.[13] The body of a gas-gap switch consists of two interleaved copper cylinders, the hollow base cylinder surrounding the solid upper cylinder, hard soldered into a thin-walled stainless steel tubular case and separated by a narrow gap. Gaseous $^4$He is introduced by heating an integral sorb pump to turn the switch on, and is removed by allowing the pump to cool, to turn the switch off. An on/off switching ratio of around 500 is typical of the simple and compact switches used in this application. By using a link with controllable thermal properties, it allows rapid cooling of the absorbent material of the larger sorption pumps. Each $^4$He precooler unit is filled with 4 l of gas (STP), and each $^3$He precooler unit is filled with 2 l of gas (STP).

### C. Split-condenser design

Chase Research Cryogenics Ltd. undertook the complete design and manufacture of this closed unit.[12] The basic design of the split condenser was arrived at empirically based on many years of experience in building $^3$He systems at Chase Cryogenics Ltd. As shown in Fig. 4, the cooler unit comprises a single cold head, and two condensers for the $^3$He gas that are thermally linked to one of the two pre-cooler units—subsystem A or B. In this way, this unit can be referred to as a "split condenser." The split condenser unit also has a tank attached to allow for $^3$He gas expansion at room temperature. This tank is mechanically mounted and thermally linked to the 4 K plate via a copper strap. The split condenser unit is filled with 1.5 l of gas.

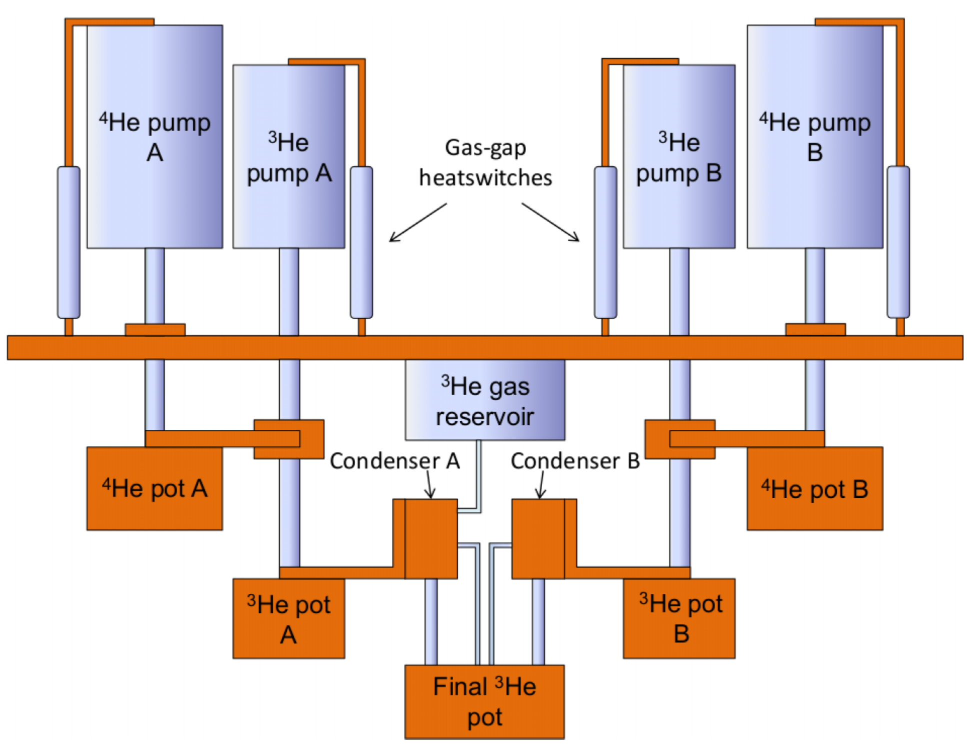


FIG. 4. Schematic diagram of the split condenser design, labelled final $^3$He pot, precooled by either subsystem A or B. Orange denotes copper, blue denotes low thermal conductivity stainless steel.

To describe the operation more fully with regard to this split condenser, we consider the phase of operation where pre-cooler A is cold and B is being recycled. $^3$He evaporating in the split condenser reservoir is re-condensed in the condenser attached to the active $^3$He module (A in this case), and returns to the reservoir by gravity, either running out of the condenser along the return capillary, or by refluxing down the vertical gas tube. Both of these return routes are likely to provide a return flow, although the capillary route is most likely dominant, due to the geometry of the condenser blocks. During this phase, subsystem B is cycled. Thermal isolation of the final $^3$He refrigerator from the warm pre-cooler B is provided by the poor thermal properties of the length of stainless steel capillary and the tube which links it to the reservoir. At the end of this phase, the pre-coolers are switched such that A is cycled while cooling is provided by subsystem B.

## III. SYSTEM OPERATION AND PERFORMANCE

### A. Cooling procedure for continuous operation

For the continuous cooler described here, the cycle procedure for a single $^4$He/$^3$He system is repeated for each subsystem (A and B) such that the third $^3$He head is continuously cooled by the side that is not being cycled. Thus, a *complete* cycle consists of cycling A, a waiting period, cycling B, followed by a waiting period before restarting. A subsystem cycle will now be described in detail. Note that during this cycle, the heat switches of the cold subsystem are heated such that there is a thermal link between the pumps and the 4 K plate, and this cold head remains below 300 mK. For example, if subsystem A is being cycled, the heat switches of subsystem B are heated to keep system B cold.

A typical cycle procedure for subsystem "B" followed by "A" is shown in Fig. 5. The pump and heat switch temperatures are shown in the upper graph, while the 1 K and 300 mK stage temperatures are shown in the lower graph. Note that during the full cycle, the final cold head (shown in red in the lower graph) is at a temperature of <300 mK throughout. There is no attempt to stabilise the temperature of the continuously cooled head in the example shown here.

The annotated cycle begins at point A by turning off the $^4$He heat switch such that the thermal link between the $^4$He pump and the 4 K plate is broken. The $^4$He pump temperature rises slowly during the time that the heat switch is allowed to cool below 12 K, at which point it absorbs the internal $^4$He gas and breaks the thermal link to the 4 K plate; in this case, this happens over 12 min. A power of 0.48 W is applied to the $^4$He pump (metal film) heater at point B until its temperature reaches 50 K (point C) after 14 min. The lower graph shows the temperature of the 1 K pot rising as gas is released from the heated sorption pump and is liquefied upon contact with the 4 K plate (a typical condensation temperature here is 3.6 K). The $^4$He pump temperature is then stabilised with a power of 48 mW.

Power to the $^3$He heat switch heater is also removed at point C. Again, this heat switch is allowed to cool for 12 min to break the thermal link to the 4 K plate before applying 0.36 W to $^3$He pump heater. It takes approximately 9 min for the $^3$He pump temperature to reach 50 K (point D), whereupon the temperature is stabilised with a power of 63 mW. The lower graph shows the temperature of the 300 mK pot rising as gas is released and liquefies via the condenser cooled by thermal contact with the 1 K pot provided by a copper strap. The final cold head remains below 300 mK due to cooling through the opposing subsystem. Both pumps are held at 50 K for 20 min.

At point E, power to the $^4$He pump heater is removed and 0.8 mW of power is supplied to the $^4$He heat switch (surface mount resistor) heater. A thermal link is therefore created between the pump and the 4 K plate as the gas-gap heat switch is activated, the pump is cooled and the 1 K pot (shown in the

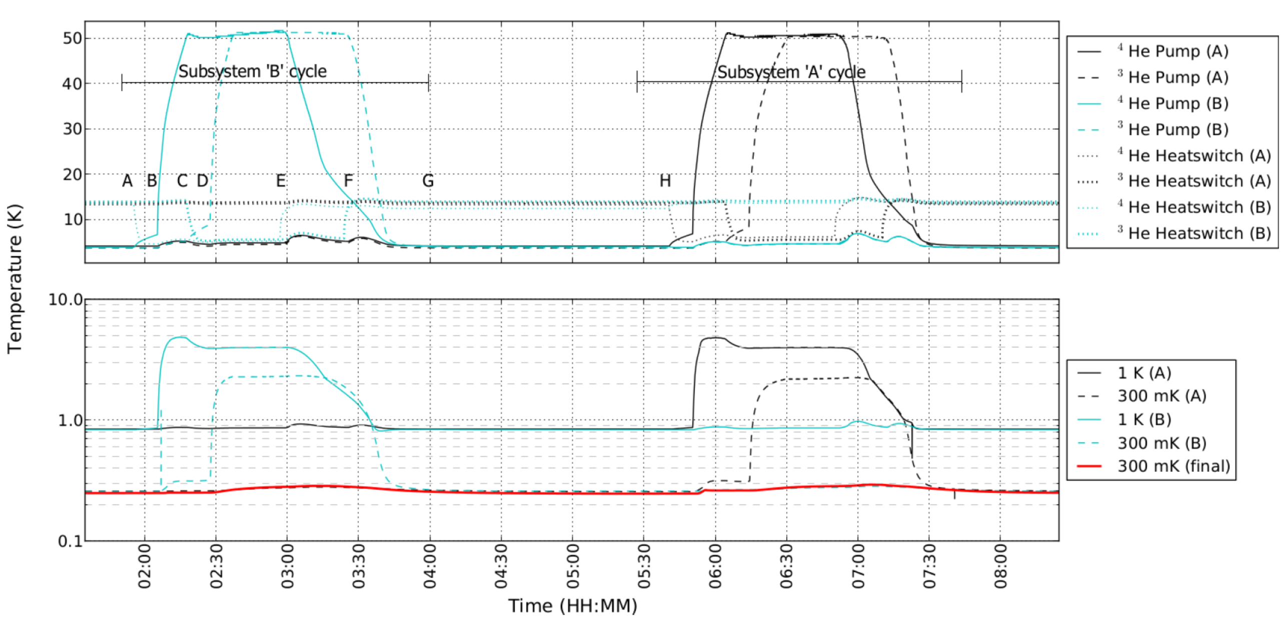


FIG. 5. Typical cycle procedure for $^4$He/$^3$He subsystem B followed by A. See text for full description of the cycle.

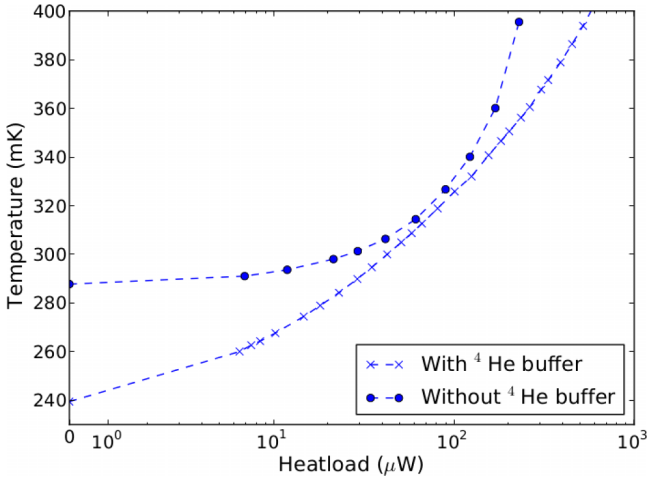


FIG. 6. Heat load curves for the cold head of subsystem B prior to the addition of the continuous cooler unit. The measurement was made with (crosses) and without (dots) liquid in the $^4$He pot that buffers the $^3$He head.

lower graph) cools as the vapour pressure above the $^4$He liquid is reduced by the activation of the sorption pump. Finally, after 27 min at point F, power to the $^3$He pump is removed and the $^3$He heat switch is switched on to cool the $^3$He pump and thereby cool the 300 mK pot of this subsystem.

The automation program is designed to wait until the 300 mK cold head reaches a pre-set temperature (300 mK for the example shown here, after 17 min) and a wait time is specified by the user to pass before it will repeat this process for the opposing $^4$He/$^3$He subsystem ("A" in this case). The representative data shown in Fig. 5 have a wait time of 2 h set between subsystem cycles. A subsystem cycle procedure shown here takes approximately 2 h; this can be shortened, though a limit is placed on the cycle length by the cooling power of the PTC and the hold time of the $^4$He pots.

Prior to the addition of the continuous cooler, the individual subsystems were tested. Both A and B had a hold time in excess of 24 h. A measurement of the heat lift of subsystem B was also made. The results of this are shown in Fig. 6. We find that if sufficient $^4$He liquid is condensed such that it remains during the full subsystem cycle, the $^3$He pot temperature is lowered from 287 mK to just under 240 mK. Similar behaviour is observed with subsystem A. We find that subsystem B has a temperature of 283 mK under a 20 $\mu$W applied heatload; sufficient to bring this system in line with the objective to build a system useful for THz detector applications.

Calibrated thermometers—silicon diodes for temperatures >4 K and 4-terminal germanium RTDs for low temperature stages—are monitored using a QMC Instruments Sub-Kelvin Temperature Controller,[14] which also controls all system heaters. To make continuous cooling at 300 mK versatile and accessible to a wide range of users who do not necessarily have experience of cryogenic techniques, full automation of the split-condenser cycling has been implemented by interfacing the control box with LabVIEW.[15] The automation of continuous cooling is available with minimal user input though it does not include full control of the PTC compressor or logging of other information from the PTC, for example compressor hours, at present. This functionality could easily be added for full remote operation. From switching on the PTC from room temperature, the total time required to begin continuous cycling is 23 h. A "sacrificial" cycle of one of the subsystems is required to achieve base temperature; this takes approximately 3 h after which normal cycling begins.

## B. Split-condenser performance

Fig. 7 shows an example of a 24 h period of continuous cooling below 300 mK. There was no user intervention during

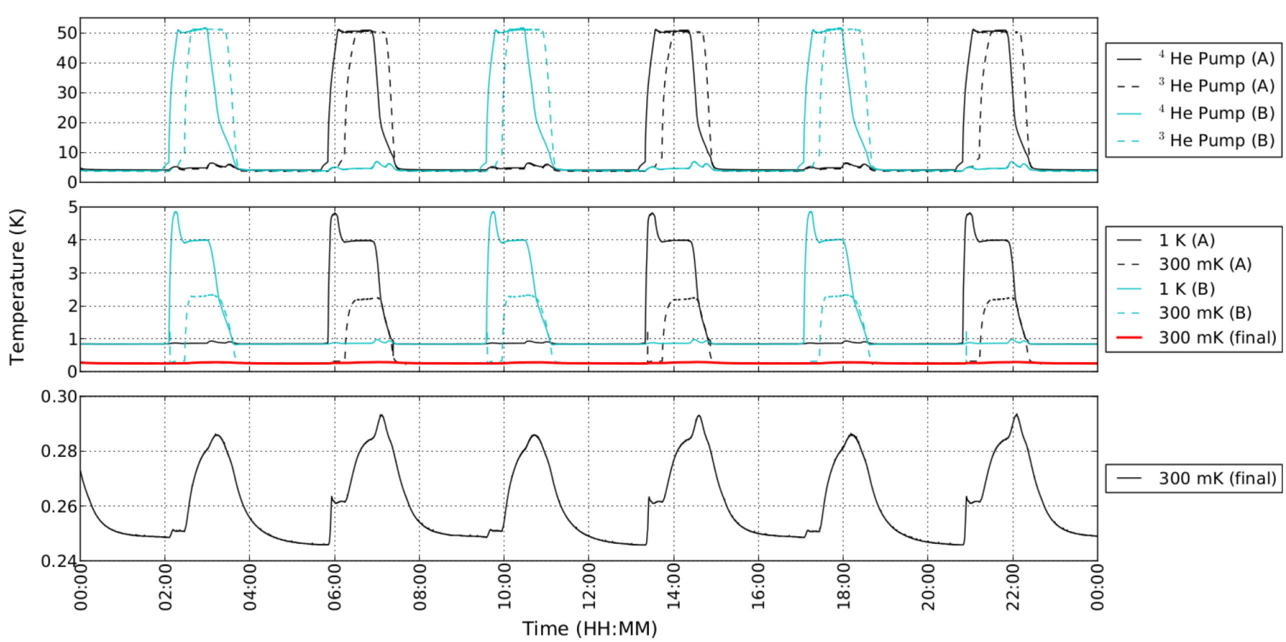


FIG. 7. An example of a 24 h period of continuous cooling with no additional heat load applied to the final $^3$He cold head. Subsystem A temperatures are shown in black and subsystem B is shown in blue. Heat switch temperatures are omitted for clarity; the variation in precooler pump temperature is indicative of their operation.

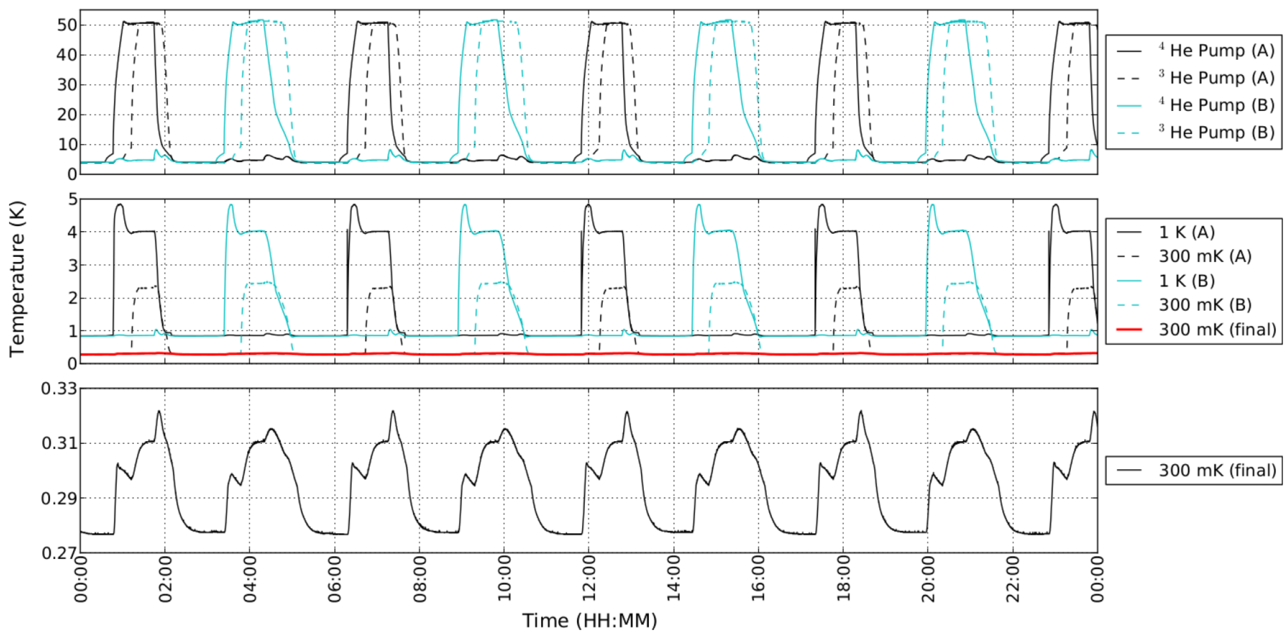


FIG. 8. A 24 h period of continuous cooling with an applied heatload of 20 $\mu$W to the final cold head.

this period. During this 24 h period there was no additional heat load applied to the continuously cooled head and no attempt to stabilise the temperature. Using a "wait period" of 2 h between subsystem cycles, the lowest achievable temperature of the final cooling stage is 246 mK. We find that there is a maximum rise in temperature, $\Delta T$, of the third head of 47 mK, i.e., the maximum temperature of the third head during a 24 h period with no additional heatload is 293 mK.

Fig. 8 shows an example of the system performance under a steady 20 $\mu$W applied heatload to the continuously cooled $^3$He head for 24 h. The period between subsystem cycles was reduced to 1 h in this case. Again, the temperature of the final cold head is influenced by the subsystem cycles with a maximum ΔT of 45 mK.

To address the origin of the approximate 45 mK ΔT that is observed over a precooler cycle, we refer to Fig. 6 which shows the temperature of the precooler unit B as a function of applied heatload prior to installation of the final $^3$He head. The cooling data shown in Fig. 7 show that a maximum temperature of 285 mK is reached by the continuously cooled head as precooler B is cycled which, from Fig. 6, indicates a heatload of 26 $\mu$W. The graph shown in Fig. 9 shows lowest temperature achieved on the continuously cooled $^3$He head as a function of applied load, i.e., the temperature that is achieved when neither precooler unit is being cycled. From this, it is shown that the temperature achieved on the continuously cooled head for zero applied load is 247 mK, but approximately 30 $\mu$W applied load is required to increase the temperature to 285 mK, as is observed during the cycle of subsystem B. The cycling precooler head temperature is increased to 2.32 K during this time.

From the geometry of the split-condenser design, the heat conduction through the stainless steel tubes and thermometry wires from the cycling condenser to the continuously cooled head is calculated to be approximately 12 $\mu$W. This is an apparent underestimate of the applied heatload of approximately one third. We attribute the additional heatload to conduction through the stationary $^3$He gas within the tubes; the thermal conduction is through this stationary gas column, as the thermal gradient along the warm gas tube on the split condenser module is in the wrong direction to allow gas convention.

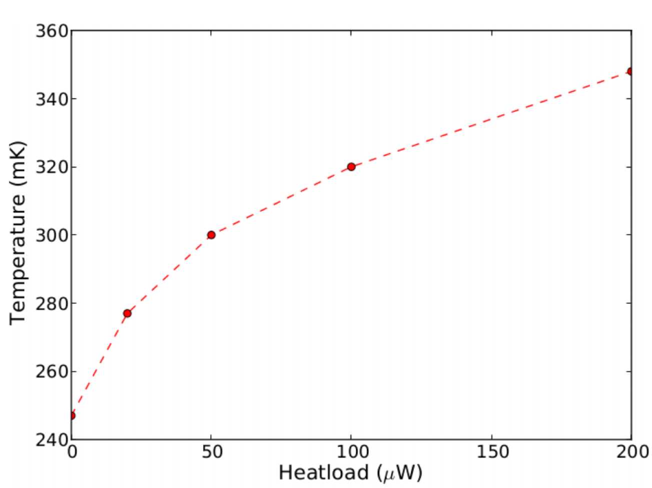


FIG. 9. Temperature of the continuously cooled $^3$He head as the heat load applied is increased where the dashed line is a guide to the eye.

## IV. TEMPERATURE STABILISATION: PID CONTROL

The results in Figs. 7 and 8 show that the temperature of the continuously cooled $^3$He head is not stable during the time that either pre-cooler subsystem is being cycled; a ΔT of 45 mK is observed. To eliminate the variation in temperature, we have implemented automatic PID control of the temperature of the continuously cooled head.

To achieve PID control, we use the scheme illustrated in Fig. 10 where the temperature adjustment is performed by a

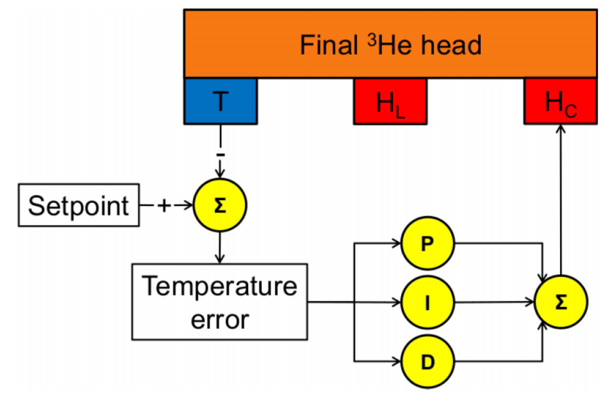


FIG. 10. Diagram to show the method by which we achieve temperature stabilisation. The sensor is a low temperature GRT (T). Continuous loading is provided by heater $H_L$, and PID control is automated with a LabVIEW program where the output is sent to a control heater $H_C$.

LabVIEW program that is run separately to the continuous cooling program, thus maintaining fully automatic operation of the system. We monitor the temperature of the continuously cooled head with a calibrated low temperature GRT thermometer using an AC resistance bridge. A setpoint is selected just above the maximum temperature expected during a cycle. The output of the PID program is sent to a 10 kΩ control heater $H_C$ mounted less than 1 cm from the sensor on the cold head. The PID control program monitors the temperature at a rate of ∼3.5 Hz, while the automation software has a lower rate of ∼0.4 Hz. In the analysis presented here, the temperatures shown for the final $^3$He head collected by the PID control program were averaged over the time period between temperature points collected by the cycling program, which is approximately nine times slower.

The resulting temperature stabilisation of the continuously cooled head is shown in Fig. 11 for a 24 h period. In this case, the set point was chosen to be 312 mK; 19 mK above the maximum temperature observed for no additional heat load applied to heater $H_L$. It should be noted that these parameters were not carefully optimised since apparent temperature stabilisation was achieved without further optimisation but careful tuning of these parameters would potentially improve performance. For the results shown in Fig. 11, the heater output was limited to 100 $\mu$W such that the system could be operated unattended without accidental runaway; Fig. 9 shows that the maximum temperature that could be reached within this limit is ∼320 mK assuming proper cycling of the precooler units.

Further to this, heater $H_L$ was used to load the continuously cooled head with 20 $\mu$W to simulate the typical thermal loading of a far infrared detector system.[7] The same PID parameters were used to stabilise the temperature at 365 mK and the result is shown in Fig. 12. The precooler cycle procedure was altered from that shown in Fig. 8 so as to avoid fast changes in temperature that lead to excursions from the setpoint. The heating procedure of the precooler $^4$He and $^3$He pumps was to reduce the initial power supplied until a temperature of 20 K is reached, whereupon the power is increased and each pump is heated to 50 K as before. By heating the pumps slowly, the gas is desorbed over a longer period and direct loading of the final cold head happens on a time scale that the PID control is able to compensate for. Similarly, the pumps are cooled slowly by turning on the heat switches gradually so as to avoid high thermal loading on short time scales.

To quantify the level of temperature stability achieved by our PID control system, we have calculated the Allan deviation of the measured set point temperature. This type of time domain analysis was originally developed to measure the system performance of atomic clocks[16] and provides information about both the stability and the noise processes that affect the measured quantity. Fig. 13 shows the result of this analysis. The Allan deviation of the measured temperature of the $^3$He cold head is calculated as a function of averaging times,

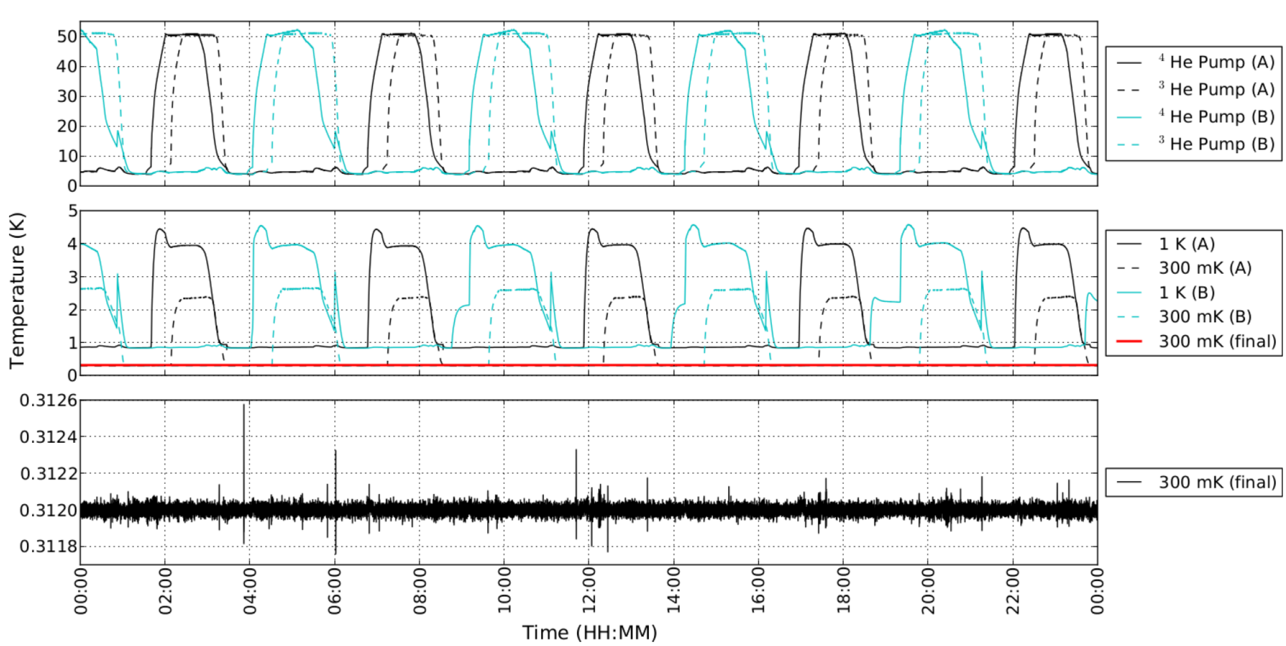


FIG. 11. A 24 h period of continuous cooling with PID control of the temperature on the final cold head.

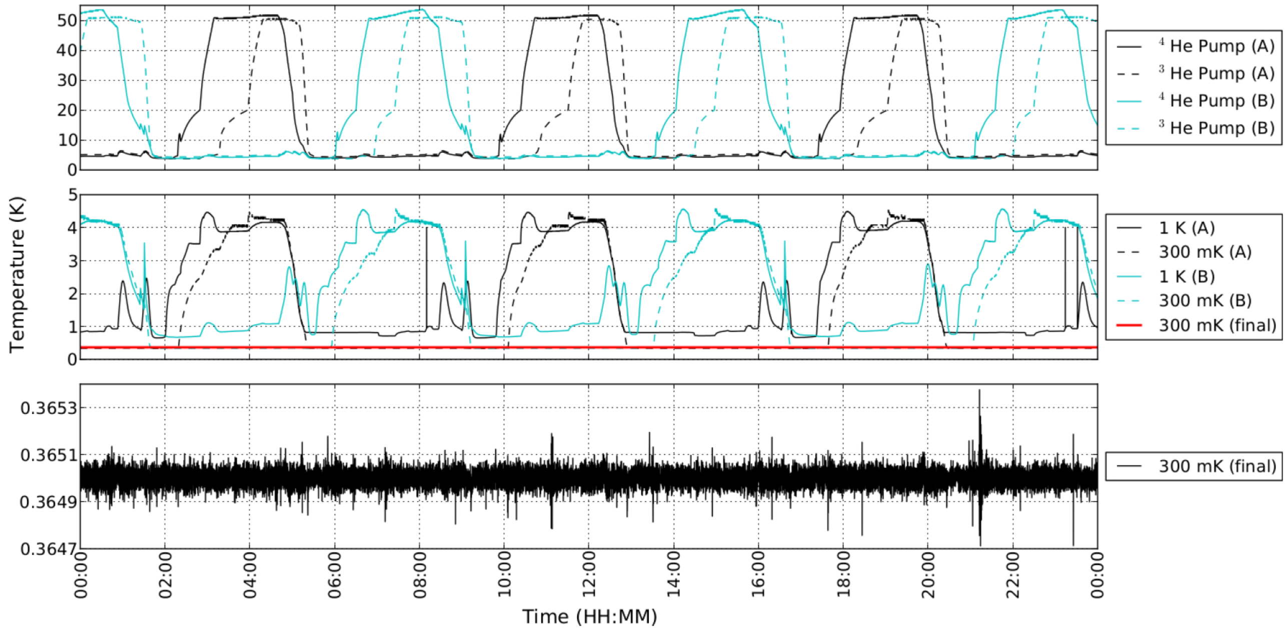


FIG. 12. A 24 h period of continuous cooling with PID control of the temperature on the final cold head at 365 mK with a constant 20 $\mu$W heatload applied to heater $H_L$.

$\tau$ (s). In general, there are four signatures that are looked for;[17] (1) a slope of $\tau^{-0.5}$, white noise, (2) a slope of $\tau^0$, $1/f$ type noise, (3) a slope of $\tau^{+0.5}$, random noise, and (4) a slope of $\tau^{+1}$ a steady drift. Analysis of this type of Allan deviation plot versus the average period, $\tau$, leads to an understanding of the system temperature stability over a range of sample averaging periods.

The stabilisation temperature for no load and 20 $\mu$W load shows a decrease in Allan deviation temperature as the averaging time increases demonstrating excellent long term stability. Examination of Fig. 13 shows that we have statistical temperature fluctuations for periods shorter than 1 min and longer than 5 min testifying to good short and long term temperature stability. On intermediate time scales, there is clear evidence of a $1/f$ type fluctuation (i.e., a slope of $\tau^0$) in the stability at the level of ∼5 $\mu$K. This could originate from an air conditioning unit in the laboratory that switches according to local conditions.

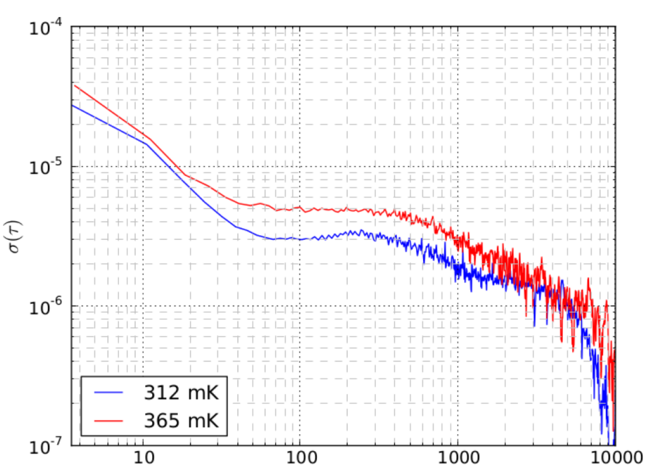


FIG. 13. Allan deviation of the PID controlled temperature of the continuously cooled $^3$He head under no additional loading (blue) and 20 $\mu$W continual load (red), $\sigma(\tau)$, plotted against the averaging time, $\tau$.

## V. CONCLUSIONS

We have designed, built, and demonstrated a continuously cooled $^3$He refrigerator that is capable of remote automated stable operation at 312 mK to within the accuracy of our readout electronics. The system uses a minimal quantity of $^3$He gas to provide continuous cooling, thereby lowering the overall cost compared to a traditional single-shot fridge with long hold time requirements. We have shown that this laboratory prototype can support a 20 $\mu$W load with a stable cold head temperature of 365 mK; enough for most THz detector applications. It is worth noting that, in testing the split condenser system, the continuously cooled $^3$He head remained at a temperature <400 mK for over three months while being operated and monitored remotely.

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