A compact cryogen-free platform operating at 1 K or 50 mK

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Abstract. We report the design and performance characteristics of a compact cryogen-free platform. The system is based around a continuous 1 K pot which operates using a small \( (10 \, \text{m}^3 \, \text{h}^{-1}) \) room temperature circulation pump. The pot cools an experimental plate to \( \approx 1.2 \, \text{K} \), and has a cooling capacity of 100 mW at a temperature \( \approx 1.9 \, \text{K} \). Cooling the pot from room temperature to \( < 2 \, \text{K} \) takes around 12 hours.

The temperature range of the platform can be lowered to \( < 50 \, \text{mK} \) with the addition of a small dilution refrigerator, using the 1 K pot as a pre-cooling stage for the circulating \(^3\text{He}\). The dilution stage has a typical (continuous) cooling capacity of 30 \( \mu \text{W} \) at 100 mK (300 \( \mu \text{W} \) at 250 mK) and is designed to operate with just 3 litres of (NTP) \(^3\text{He}\).

1. Introduction

The cryogen free dilution refrigerator\cite{1} has been an enabling technology for a range of experimental applications. The rapid uptake of these machines, particularly in the field of quantum information processing, has been driven by their ease of use, large experimental plates and the ability to integrate superconducting magnets\cite{2}. The fact that these systems can be designed without an inner vacuum chamber means installing experimental services can be much more straightforward, and the desire to maximise the experimental payload has led to the design of ever larger and more powerful systems for these applications\cite{3}.

An alternative application space for milli-kelvin platforms, that has traditionally been satisfied with Adiabatic Demagnetization Refrigerators (ADRs)\cite{4} or (complex) \(^3\text{He}\) refrigerators\cite{5}, is the development of photon detectors. For these applications the cooling capacity requirements at the milli-kelvin stage are much less demanding, so a small dilution refrigerator system would be suitable, likely with the added benefits of: continuous operation; lower base-temperatures; higher cooling-powers; and no requirement for a superconducting magnet (unless an experimental magnet is desired).

Dilution units with modest base temperature and cooling power requirements can be designed to operate at low \(^3\text{He}\) circulation rates. This low circulation rate constraint places a limit on the allowable power dissipation at the still. Increased cooling capacity at temperatures \( \approx 1 \, \text{K} \), which may be desirable for operating low-temperature amplifiers or microwave filters, can be provided by an additional \(^4\text{He}\) refrigeration stage (a ‘1 K pot’)\cite{6}.

Additionally, a cryogen-free 1 K pot based system is useful in its own right: e.g. as a large sample-area platform to develop electronics that will subsequently be installed on the still of a
dilution refrigerator; or as an alternative experimental platform to traditional (wet) Variable-Temperature Inserts (VTIs), where the available sample space is often limited.

2. System design
The top-level design concept for these systems is similar to that described previously[2], with a single vacuum space, however the size of the experimental plates has been reduced to keep the system compact. The cold environment is generated by a pulse tube cooler from Sumitomo[7] which has a remote rotary valve and a nominal cooling power at the second stage of 0.9 W at 4.2 K.

The system is configurable either as a ‘1 K’ platform, or an additional dilution refrigerator stage can be added below the 1 K plate, figure 1. In the 50 mK configuration the still of the dilution refrigerator is in mechanical contact with, but thermally isolated from, the 1 K plate.

It is possible to integrate an experimental superconducting magnet, cooled by the pulse tube via a high thermal-conductivity link[2].

2.1. Pre-cooling
To simplify the operation of the system (and the gas handling system, section 2.2) the cool down of the refrigerator is designed to be automatic (rather than automated). The pre-cooling from room temperature is affected by a heat switch, section 2.1.1, for the 1 K plate, and a heat pipe, section 2.1.2, for the mixing chamber plate (when the dilution stage is installed).
2.1.1. Heat switch  Heat switches relying on the difference in thermal contraction between materials have been known for some time[8] and this principle has been used to manufacture gas-gap heat switches (GGHS) with small separations between conductors[9]. We have developed a robust manufacturing process for such thermal-contraction GGHSs which enables room temperature gaps between conductors to be zero[10]. A small adsorption pump (sorb), coupled to the cold end of the switch, is used to ensure that any residual gas is removed from the switch when the system is cold. During cool down, the conductance of the switch (and hence the heatload into the cold end) is sufficiently high that there is no need to actively temperature control the sorb, figure 2.

2.1.2. Heat pipe  Heat pipes[11] can provide a very high thermal conductance over a selective temperature range, and have been shown to assist with the cool down of cryogen-free systems incorporating large magnets or experimental payloads[12]. We have deployed a helically-coiled-tube, gravity-driven heat pipe design (to minimise the residual conducted heat load to the mixing chamber plate) linking the 1 K plate and the mixing chamber plate, with an additional condensing heat exchanger at the PT2 stage. Using neon as the working fluid allows the mixing chamber plate to pre-cool to $\sim 25$ K (in around six hours, once the PT2 stage has reached 25 K and the heat pipe is operational). Circulation of the mixture through the dilution circuit cools the system to temperatures below this.

Often heat pipes can be self-regulating, with the heat load at the condensing stage from the working fluid being sufficient to keep the system at its optimal operating temperature. Should the cooling power at the condensing stage (the PTR) be greater than the applied heat load, the heat pipe can be kept at its optimum temperature by applying additional heat. During the cool down of the system this situation can occur when the mixing chamber plate has cooled close to 25 K and the heat load on the condensing stage starts to fall; the additional heat can be applied automatically using the alarm and relay features of the temperature controller, a Lakeshore 372[13].

This technique has been verified with an additional mass of $\sim 3$ kg attached to the mixing chamber plate to simulate a pressure cell for beam-line applications.
2.2. Circulation circuits

The automatic operation of the system extends to the two circulation circuits, the basic layout of which is shown in figure 3. The details of each circuit will be described in the following sections.

2.2.1. $^4\text{He}$ gas handling system

As $^4\text{He}$ is relatively inexpensive, only a simple gas handling system (GHS) is required. A tank volume (∼ 15 L) is connected directly to the exhaust of the circulation pump and charged at room temperature to a pressure ∼ 900 mbar. As the system cools and the gas is liquefied in the pot, the tank, and hence condensing, pressure drops. An equilibrium state is achieved once the flow rate into the system (set by the value of the condensing impedance and condensing pressure) balances the rate at which $^4\text{He}$ is boiled from the pot (determined by the total heat load into the 1 K stage).

2.2.2. $^3\text{He}/^4\text{He}$ gas handling system

Whilst a similar approach to the $^4\text{He}$ GHS could, in principle, be followed for the $^3\text{He}/^4\text{He}$ GHS this would be rather inefficient in the use of $^3\text{He}$. When operating at base temperature an ideal dilution refrigerator system will be circulating pure $^3\text{He}$. The condensing pressure will always be finite, and so buffering the condensing line with a tank volume could mean (at current prices) several thousand € of $^3\text{He}$ ‘sitting’ in the tank.

To use the $^3\text{He}$ more efficiently the storage tank should be empty in operation, to accomplish this in an automatic fashion the storage tank is connected to the front of the circulation pump via a flow restrictor (so that the condensing pressure can rise only slowly). The back of the pump is connected to the tank via a check valve (sensitive to the relative pressure difference between the condensing line and tank) which can discharge the condensing line to the tank quickly, should the condensing pressure rise above a threshold value. The size of the tank is then chosen (here a ∼ 50 L tank for ∼ 15 L of mix) such that the condensing pressure is automatically limited to the desired value, 700 mbar in this case. The system handles well the large changes in flow that occur as the main impedance cools, as well as the rapid liquefaction of the $^3\text{He}/^4\text{He}$ mixture once the 1 K pot is cold, figure 4.

3. Cryogenic performance

3.1. 1 K cooling loop

The pot has a free volume of ∼ 8 cm$^3$ and is coupled to a copper plate 180 mm in diameter. The pot pumping line incorporates a counter-flow heat exchanger to thermalise the returning $^4\text{He}$,
and the cooling capacity available on the plate, when circulating with a 10 m³ h⁻¹ dry pump, is as shown in figure 5.

For operation as a stand-alone ‘1 K’ system, closed-loop temperature control of the plate is possible, at ≈ 1.3 K the measured stability was 1.30006 ± 0.00031 K.

3.1.1. Operation with ³He  It is also possible to run the cooling loop with ³He, rather than ⁴He. Due to the higher vapour pressure of ³He, lower temperatures can be attained without altering the system configuration. Initial measurements have shown a base temperature of below 800 mK.
3.2. 50 mK stage
The dilution unit has a diameter of $< 40$ mm and an overall length of $\approx 150$ mm. The mixing chamber is connected to an experimental plate 150 mm in diameter.

The circulating $^3$He is liquefied at the 1 K stage before heat-exchange with the liquid in the still, the continuous heat exchanger and two discrete (Ag sinter) heat exchangers prior to dilution in the mixing chamber.

The small size of the dilution unit means only $\sim 3$ litres of (NTP) $^3$He are required to operate the refrigerator (with a total mixture volume $\sim 12-13$ litres). The $^3$He is circulated using a 40 m$^3$ h$^{-1}$ dry pump.

The system attains base temperatures below 40 mK and typical cooling capacities at 100 mK of around 30 $\mu$W (rising to around 300 $\mu$W at 250 mK), as measured in vacuum on the experimental plate, figure 6.

The optimal $^3$He circulations rate is $\approx 200 \mu$mol s$^{-1}$ which equates to a required heat input to the still $\approx 5$ mW. Without the 1 K pot, this would be the upper limit on the allowed dissipation at temperatures around 1 K. The additional heat load on the 1 K pot from the circulating $^3$He is commensurate with the power applied to the still, whereas the cooling power available from the 1 K pot is much higher, figure 5, and so the addition of the $^4$He stage means an order of magnitude higher power dissipation at temperatures around 1 K is possible compared with using the still alone.

The relatively large background heat load into the mixing chamber, from the fits in figure 6 $\sim 4$ $\mu$W, is due to the heat conducted through the support structure from the 1 K stage. The desire to make the support structure stiff and able to support heavy experimental payloads (10s of kg), coupled with the fact that these continuous cooling capacity figures (and the large cooling capacity at 1 K for thermalising experimental services) compare very favourably with the performance offered by ADR or $^3$He systems, means that no attempt has been made to further reduce the conducted load.

The (open loop) temperature stability of the mixing chamber stage is $< 20$ $\mu$K.

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