A compact, low-power <1K cooling platform for superconducting nanowire detectors

Emily Ronson, Simon Chase and Lee Kenny
Chase Research Cryogenics, Cool Works, Unit 2 Neepsend Ind Est, Parkwood Road, Sheffield S3 8AG, United Kingdom;
emily.ronson@chasecryogenics.com

Abstract. Superconducting nanowire single photon detectors (SNSPD) with high detection efficiency, low dark count rate, small timing jitter and short recovery times require cryogenic cooling. Detector performance is strongly dependent on temperature and though many detectors will operate at ~4K, lower temperatures offer significant performance gains. Fortunately, the technology for sub-Kelvin cooling is now mature and products are available that offer simple operation, with reliable and repeatable performance at relatively low cost. In this paper we review performance data from tests on more than 45 individual sub-Kelvin modules manufactured by Chase Research Cryogenics. We compare modules of different sizes and discuss how modules can be scaled to achieve a range of technical specifications for specialised end-user applications.

1. Introduction
In the last few years, Chase Research Cryogenics has designed and built many closed-cycle 4He modules for customers with a wide range of user applications. These modules vary in size, weight, power consumption, heat lift capacity, base temperature and run time. In this paper three differently-sized 4He modules are discussed, the 4 STP litre modules are designed for a run time of approximately 10-12 hours under a 100μW load, the 10-12 STP litre modules are designed for a run time in excess of 20 hours under a 100μW load, and the 33 STP litre modules are designed to run for more than 12 hours with a 1000μW load. All three module sizes are designed to run at a temperature below 1K.

The run time is determined primarily by the total quantity of 4He in the module. After condensation to liquid, the 4He is evaporated by the combined load from the user’s apparatus (e.g. SNSPD array) being cooled by the module, and by base load. The base load encompasses all mechanisms for evaporating 4He that are not directly due to the user’s apparatus. These mechanisms include, but are not limited to, heat conduction up the pumping tubes, superfluid film creep and radiative loading on the head of the module. Their contribution to base load is determined by the design parameters of the module, which we discuss in this paper. A simple mathematical model of the helium condensation process, as described by Pobell [1], has been used to estimate the cooling power and base load for each module size.

A wide range of SNSPD devices require cryogenic cooling, though they do not necessarily impose high cooling power requirements [2]. Sub-Kelvin 4He modules with a short initial cool down and time long run time may be optimal for many low-temperature detector applications, and we discuss the best way to achieve this specification.

2. Operation
The 4He modules described in this paper are compact sealed units that are simple to operate. They consist of a cold head (where the temperature reaches below 1K); a film burner, which contains an orifice to control super fluid film creep; a main plate; and a cryopump that contains activated charcoal. A gas gap heat switch is connected between the cryopump and the main plate. The main plate is pre-cooled via a
thermal link to either a liquid $^4$He (L4He)-cooled plate or a ‘dry’ mechanical pre-cooler (e.g. a Gifford-McMahon or Pulse tube).

The operation of $^4$He modules is well described in the literature [3,4]. Basic procedure entails pre-cooling the module’s main plate and head to below 4.2K. The cryopump is then heated in order to drive the $^4$He gas off the charcoal and condense it into the head, which is mounted lowermost during operation. Once all the $^4$He has condensed, the pump heater is turned off and the gas gap heat switch is turned on to cool the pump to the temperature of the main plate. This allows the gas to be adsorbed into the pump once again and the liquified $^4$He in the head continues to cool until its vapour pressure is in equilibrium with the internal pressure of the module. At this point the module is running at its base temperature. The module will keep running until the liquid $^4$He in the head is exhausted, when it can be recycled by reheating the pump. Recycling takes approximately 1 hour. The temperature of the head while running will depend on design parameters and applied loads.

3. Methods and Material

Tests have been carried out to verify the performance of more than 45 $^4$He modules manufactured over the past ~5 years. These modules are in three very different sizes, containing 4, 10-12 and 33 STP litres of $^4$He gas. The 4-litre module has the shortest tubes connecting the head to the pump. The 10-12 litre and 33 litre modules are of similar design with off-centre pumps and longer pump tubes, but differing size pumps and heads. Across all three modules, the size of the superfluid containing orifice, and the diameter of the pump tubes, both increase with module size. Dimensional parameters can be found in Table 1, and images of CAD models in Figure 1.

![Figure 1. CAD models of 4, 10-12 and 33 litre modules (different scales).](image)

Each test was carried out in a L4He-cooled cryostat. Temperature measurements were made using a ruthenium oxide temperature sensor on the module’s head, a diode or ruthenium oxide temperature sensor on the film burner, a diode on the pump and a diode on the switch. Resistive heaters on the pump and the heat switch were used to control the module’s operation. A resistive load heater was also mounted on the head of each module, for testing the response to loading by varying the voltage.
Data were collected using either Lakeshore Cryotronics or custom-made thermometry equipment, with software control via a Labview VI.

### Table 1. Dimensional Parameters.

| Dimensional Parameters | 4 litre | 10-12 litre | 33 litre |
|------------------------|---------|-------------|----------|
| Module Height (mm)     | 220     | 220         | 237      |
| Main plate diameter (mm)| 50     | 89          | 127      |
| Weight (g)             | 450     | 1400        | 3063     |

Each module was tested against the customer’s specific requirements, so each test sequence varied slightly. When possible, load response data were acquired by applying a load to the head and waiting for the temperature to stabilise, then repeating this process over a specified range of loads. Once the load response test was complete the module was run under a customer-specified load to expiry, which enabled us to verify that the module met the run-time specification. The run time was calculated as the total length of time the module head spent at a temperature below 1K. The typical loading specification for 4 litre and 10-12 litre modules was 100μW and for 33 litres was 1000μW. When possible, a second run was completed with no applied loads in order to estimate the base load on the module.

Our mathematical model was used to estimate the condensation efficiency, for each module size, from the total number of moles of 4He in the module, the internal volume, and the temperatures of both the head and the pump during condensation. The temperature values used in the model were averages of the measured values for each size module. The cooldown to base temperature was also modelled to calculate the total cooling power available to the module at the start of the run. The base load was then estimated from the total run time when there was no applied load, i.e assuming the condensed helium charge was consumed solely by the base load.

### 4. Results

#### 4.1 Experimental data

Table 2 shows the average head temperatures for some standard loading conditions on the modules. The 4 litre and 10-12 litre modules were all tested with both no load and 100μW load, and the 33 litre modules were tested using a higher loading condition at 1000μW.

| Temperatures (mK)   | 4 litre | 10-12 litre | 33 litre |
|---------------------|---------|-------------|----------|
| No-load             | 854.6±20.9 | 830.1±23.3 | 802.5±14.4 |
| 100μW load          | 905.9±13.1 | 866.8±23.6 | n/a      |
| 1000μW load         | n/a     | n/a         | 957.3±7.2 |

| Run time (hours)    | 4 litre | 10-12 litre | 33 litre |
|---------------------|---------|-------------|----------|
| No-load             | 14.2±5.0 | 43.2±2.8    | n/a      |
| 100μW load          | 11.4±1.4 | 31.2±4.6    | n/a      |
| 1000μW load         | n/a     | n/a         | 13.1±1.8 |

Table 3 shows the run time of modules under different loading conditions, in each case the module was run to expiry under the stated load. Note that the largest module was designed to run under significantly higher loading conditions and at low temperatures.
Figure 2, Figure 3, and Figure 4 show the load response data for each module size. Figure 2 contains data from 8 individual 4 litre modules, Figure 3 contains data for more than 30 individual 10-12 litre modules, some of which were tested several times with different loading conditions, and Figure 4 shows data for 7 individual 33 litre modules. In Figures 2 and 3, lines are fitted to the data using least squares, whereas in Figure 4 the data are fitted with a power function. All three fitted relationships are compared in Figure 5, which shows 95% confidence intervals for each relationship.

**Figure 2.** 4 litre module load response to loading.

**Figure 3.** 10-12 litre module response to loading.
Figure 4. 33 litre module response to loading.

Figure 5. Comparison of loading responses for different module sizes.

4.2 Modelled Results
Table 4 shows the estimated total cooling power and base load for each module size. Note that higher cooling powers would be expected if the modules were pre-cooled using a mechanical pre-cooler, as the condensation conditions are more favourable [5]. These modules would run for significantly longer in a liquid-cryogen-free system with a mechanical pre-cooler.
Table 4. Calculated cooling powers for each size module, with a L4He-cooled cryostat

|                  | 4 litre | 10-12 litre | 33 litre |
|------------------|---------|-------------|----------|
| Cooling Power (J)| 8.092   | 27.95       | 66.244   |
| Base load (mW)   | 0.104   | 0.162       | 0.527    |

In Figure 6 we explore the relationship between the size of the orifice that controls superfluid film creep and the observed performance of the modules. The orifice sizes are normalised in ratio to the orifice of the 10-12 litre module; the 4 litre module has the smallest orifice and the 33 litre module the largest orifice. A smaller orifice constrains the film creep more, which in turn reduces the base load. However, a smaller orifice also results in a higher head temperature at a given load, and a steeper response to applied loads.

Figure 6. Relationship between orifice size and various parameters.

5. Discussion
The physical dimensions of the modules considered here are not scaled in direct proportion to the volume of 4He in the module. This makes some comparisons between the different module sizes indicative rather than quantitative. For example, the total cooling power of the module does scale in proportion to the module’s 4He volume, but the base load, which determines the run time of the module, does not (Table 4). That is because the base load depends strongly on the orifice size and on other physical dimensions that are not in scale with the 4He volume.

The 4-litre module has been designed as part of a continuous cooler, in which a pair of modules, cycling in antiphase, alternately cool a cold head that stays below 1K indefinitely [6]. Each module needs a low load and short run time; as a minimum it must run for the length of time it takes to recycle the other module. So, in principle this module could be made even smaller as the run time could be much shorter than 12 hours. Alternately, the orifice size could be made larger to reduce the base temperature, while sacrificing run time.
For the 4 litre modules tested here, the orifice was manufactured using a different method to the other modules, which resulted in greater variability between individual modules. The confidence intervals in Figure 5 are larger than the other modules, and the standard deviations of the run time and head temperature are larger in Table 2 and Table 3.

The 10-12 litre modules are a standard product; over 30 have been made and so their performance is very well characterised. These modules are suited to low-load applications requiring long run times. The 10-12 litre module can be configured to bolt directly onto a very small, low-powered GM pre-cooler that uses a compact air-cooled compressor. When pre-cooled in this way their run time is increased by approximately 25% [5].

The 33 litre modules are designed for higher loading applications. This module requires a larger mechanical pre-cooler as the peak power consumption is high. The module is also too heavy to bolt directly onto the mechanical pre-cooler, which makes the cryostat design more complex.

When considering the factors that contribute to the base load in the different modules, losses due to heat conduction between head and pump are not thought to be a dominant component of the base load [3]. Most of the heat conduction occurs along the tubes between the head and the main plate as the temperature gradient is greatest between these points whilst the module is running. The tube lengths and wall thickness are similar in each module design, and for comparison between module sizes can be considered effectively constant. The tubes between the pump and the main plate do vary in length and size between the modules, but this will have only a small effect on heat conduction because when the module is running, the heat switch is on, and the pump and main plate are very close in temperature.

The radiation load on the head is proportional to the surface area of the head, which increases with module size. However, each module was tested in a L4He pre-cooled cryostat with similar configuration and radiation shields at 4K and 77K, so external loading can be considered effectively constant. Internal radiation loading due to the ‘hot’ pumps will differ as the larger pumps have a larger thermal mass. The pump is located under the main plate opposite the head for each module, so direct radiation to the head is limited. When the pump is hot and radiating onto the head, gas convection is cooling the head, so the net effect of the radiation is very limited. While the module is running the pump is cold and has very low thermal emission.

The flow of helium from the cold head to the cryopump can be split into two components, superfluid film creep and gas flow. The orifice constrains the creep of superfluid helium, which is independent of loading conditions but depends on the true circumference of the edge of the orifice. In principle a ‘good’ orifice should have a knife edge so that its circumference is well-defined e.g. there is minimal surface roughness at the edge [7]. At low applied loads the quantity of helium leaving by superfluid film creep is much greater than by gas flow. A smaller orifice restricts the superfluid creep more and results in a lower base load, as shown in Figure 6. At higher applied loads a greater proportion of helium leaves the head by gas flow, the rate of which will depend on the area of the orifice. When the orifice is small and the load is large, the orifice also restricts the gas flow by trapping hot gas. This causes a larger temperature rise in response to loading, as observed in Figure 5 for the 4 litre module. The 33 litre module has a larger orifice that does not restrict the gas flow for high loads, but it produces a larger superfluid film creep and results in a higher base load, reducing the overall run time.

Our results illustrate the trade-offs between different performance parameters, which must be optimised for the specific application. For many SNSPD applications the loading conditions are minimal and a small module offering quick cool down and warm up, allowing experiments to be run over short periods of time, may be most useful. Commercial SNSPD products need a well characterised module with reliable and repeatable performance, ideally that can recycle overnight or run continuously. Such
systems will seldom be opened or warmed up to room temperature. Both the 10-12 litre and 4 litre modules offer simple operation with low power consumption, both can be mounted either directly to a mechanical pre-cooler, or to an interface plate with thermal link to the pre-cooler.

6. Conclusion
In this paper we have shown that the characteristics of $^4$He sub-Kelvin modules are well understood and it is possible to design modules that are optimised for specific applications. Increasing the volume of helium in the module increases the total cooling power available, but larger modules require larger mechanical pre-coolers and more complex cryostats. Increasing the size of the superfluid creep-controlling orifice will increase the base load and decrease the run time, but also decrease the running temperature and reduce the temperature response to loading. These characteristics must be traded off to optimise the performance of the module for the application. For commercial applications, overall cost, reliability, reproducibility, and simplicity of operation may be as important as overall performance.

References
[1] Pobell F. Matter and methods at low temperatures. Berlin: Springer; 2007 Feb 15.
[2] Dauler EA, Grein ME, Kerman AJ, Marsili F, Miki S, Nam SW, Shaw MD, Terai H, Verma VB, Yamashita T. Review of superconducting nanowire single-photon detector system design options and demonstrated performance. Optical Engineering. 2014 Jun;53(8):081907.
[3] Devlin MJ, Dicker SR, Klein J, Supanich MP. A high capacity completely closed-cycle 250 mK 3He refrigeration system based on a pulse tube cooler. Cryogenics. 2004 Sep 1;44(9):611-6.
[4] May AJ. Closed-Cycle Sorption Coolers and Tiltile Miniature Dilution Refrigerators for Astrophysics (Doctoral dissertation, The University of Manchester (United Kingdom)).
[5] Chase ST, Ronson EG and Kenny LC. Compact, add-on sub-Kelvin modules extend the working range of 4K mechanical pre-coolers to temperatures below 1K (LTD/18 in press)
[6] Chase ST, Brien TL, Doyle SM, Kenny LC. Pre-cooling a 3He/4He dilutor module with a sealed closed-cycle continuous cooler. InIOP Conference Series: Materials Science and Engineering 2019 Apr (Vol. 502, No. 1, p. 012134). IOP Publishing.
[7] Lau J, Benna M, Devlin M, Dicker S, Page L. Experimental tests and modeling of the optimal orifice size for a closed cycle 4He sorption refrigerator. Cryogenics. 2006 Nov 1;46(11):809-14.