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WORLD LEADERS IN SUB-KELVIN CRYOGENICS

Compact, add-on sub-Kelvin modules extend the working range of 4K mechanical pre-coolers to temperatures below 1K

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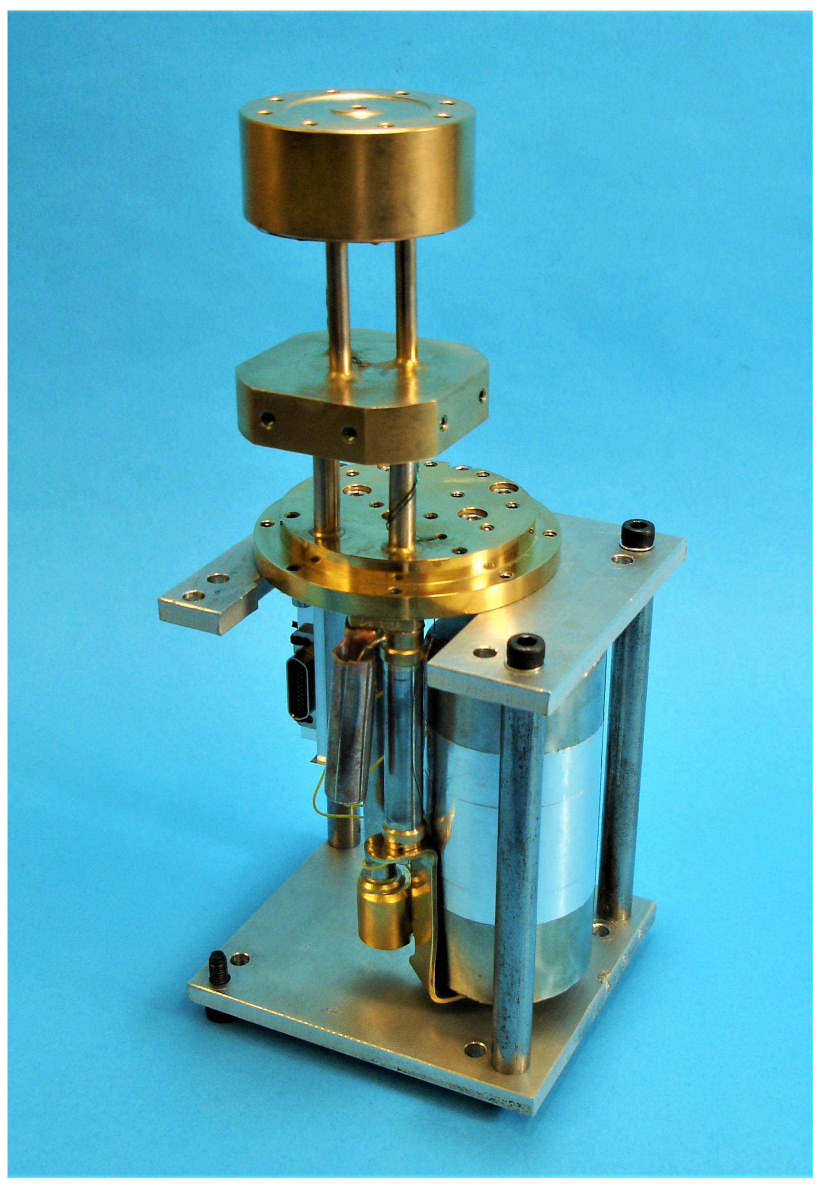
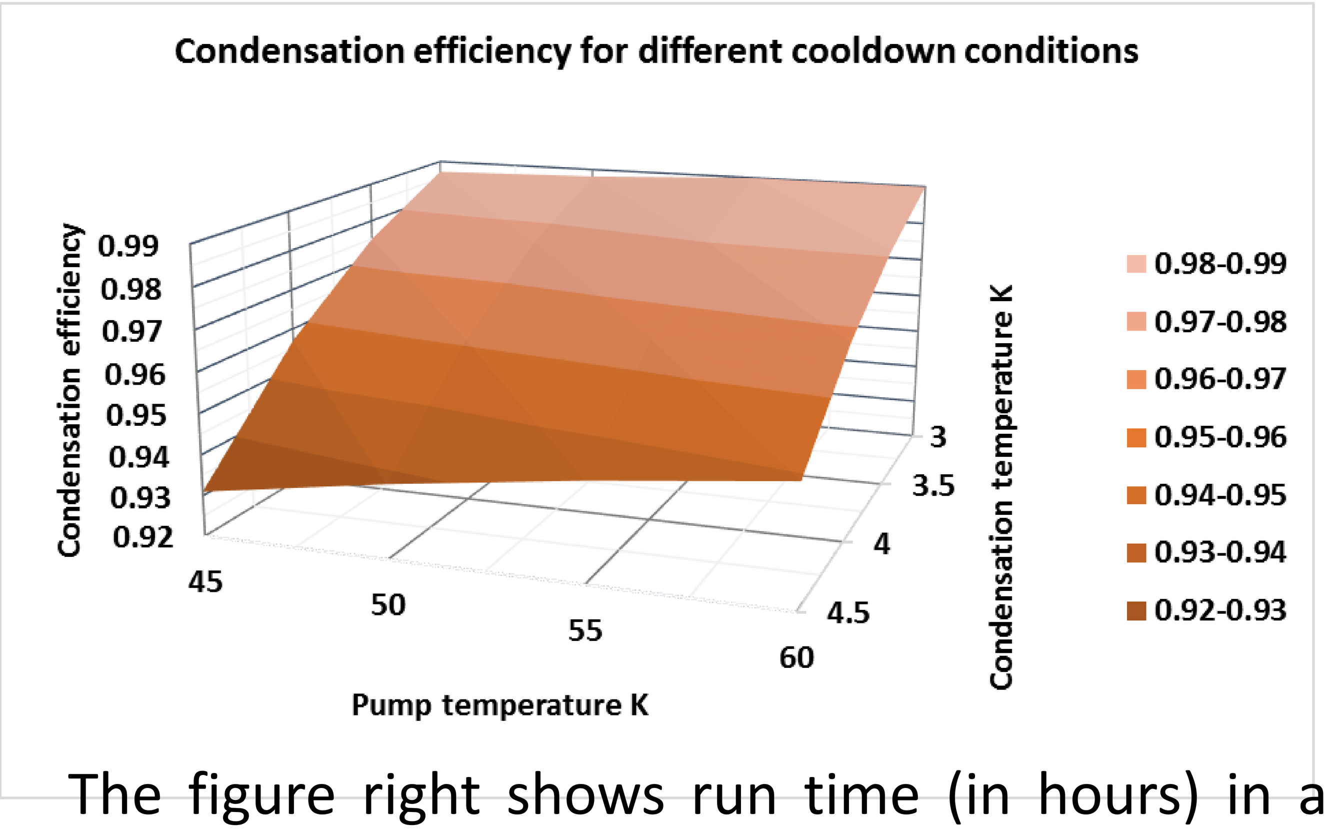


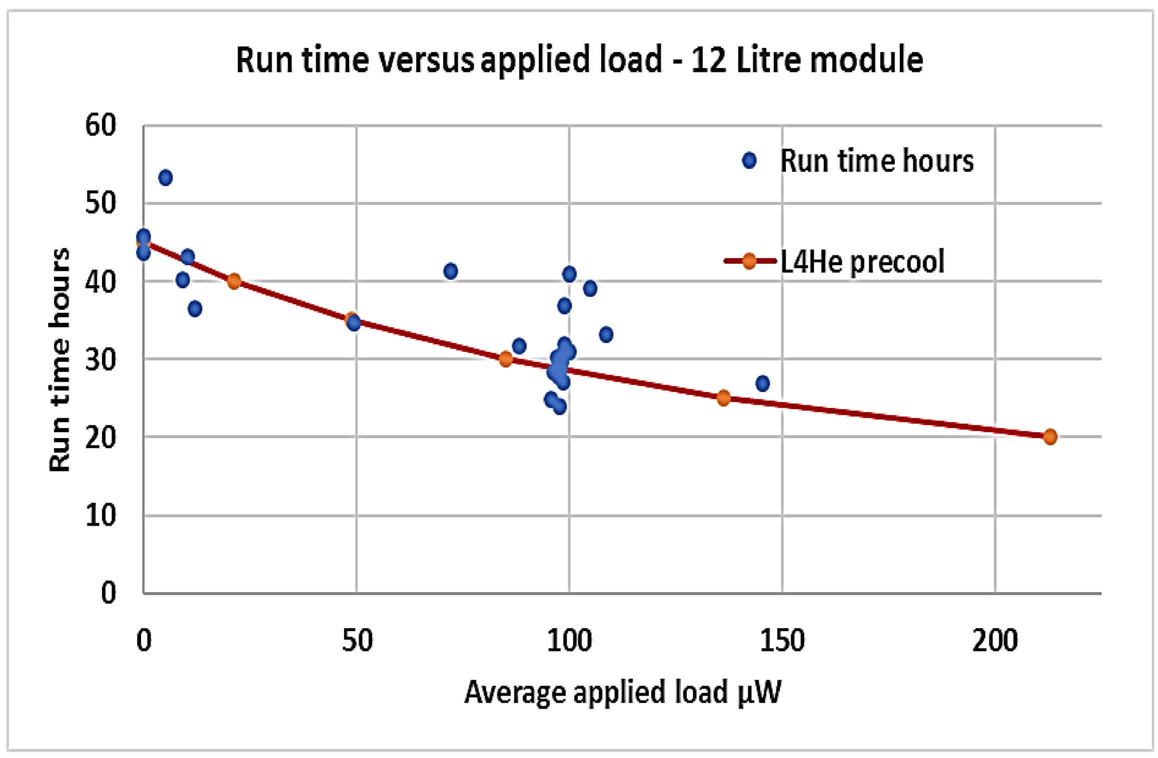
Abstract. The technology for low-power sub-Kelvin cooling is now established and products are available that offer simple operation, with reliable and repeatable performance at relatively low cost. Self-contained, sealed, sub-Kelvin modules can be added-on or retro-fitted to low-power mechanical (GM or PT) pre-coolers to extend their operating temperature below 1K. This technology offers fully automated operation, requires little or no cryogenics expertise and has superior performance compared to pre-cooling with liquid cryogens. In this paper we present data from testing more than 30 ^{4}He sub-Kelvin modules of identical design, and discuss some of the factors that determine reproducibility and reliability as well as overall performance.

Sub-Kelvin ^{4}He modules can be manufactured in different sizes to suit user requirements. A module containing 12 litres STP ^{4}He will lift at least 100µW of load, at a temperature <1K, for a run time well in excess of 20 hours before recycling. It will operate with a GM pre-cooler having only 100mW of cooling power at 4K. GM coolers of this type use compact, air-cooled compressors running on single phase electrical supply, with total power consumption ~1kW.

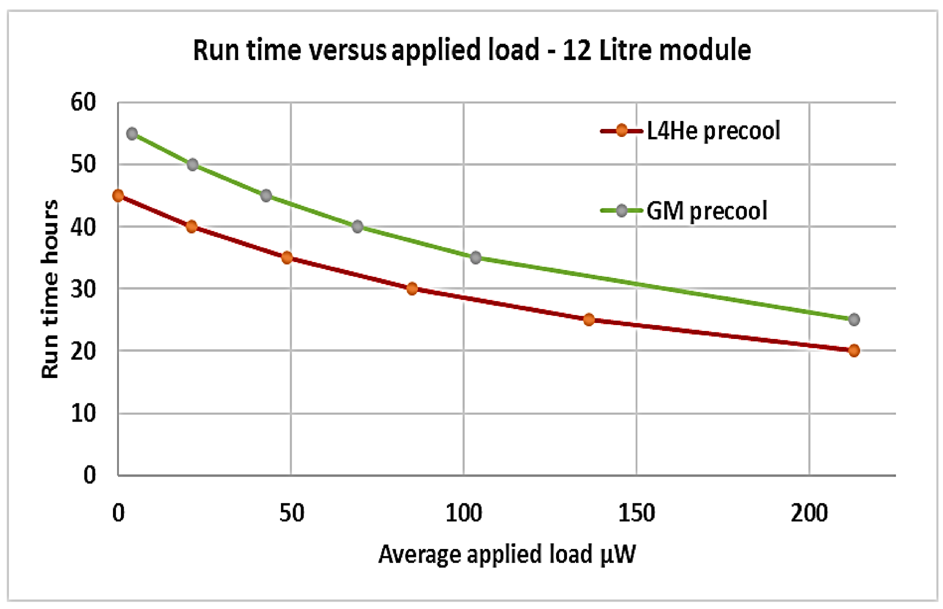


The ^{4}He condensation process can be mathematically modelled to calculate the expected condensation efficiency, given the number of moles of ^{4}He in the module, the internal volume, the condensation temperature and the pump temperature during condensation. Model results are shown left. The cooling power available at the final running temperature is estimated by modelling the ^{4}He consumed during the cool down to the running temperature. For the ^{4}He modules described here total cooling power available was estimated to be on average 27.9 Joules for L4He pre-cool conditions, and 34.5 Joules for GM pre-cooler conditions.

The figure right shows run time (in hours) in a L4He cryostat, plotted against average applied load (in µW). Data points are for ~30 individual ^{4}He modules run under different load conditions. When pre-cooled with L4He these modules achieved average base temperatures of 825±20mK under no load, rising to 858±26mK under an applied load of 100µW. Loaded run times were typically ~29±3 hours, though could be more than 40 hours.

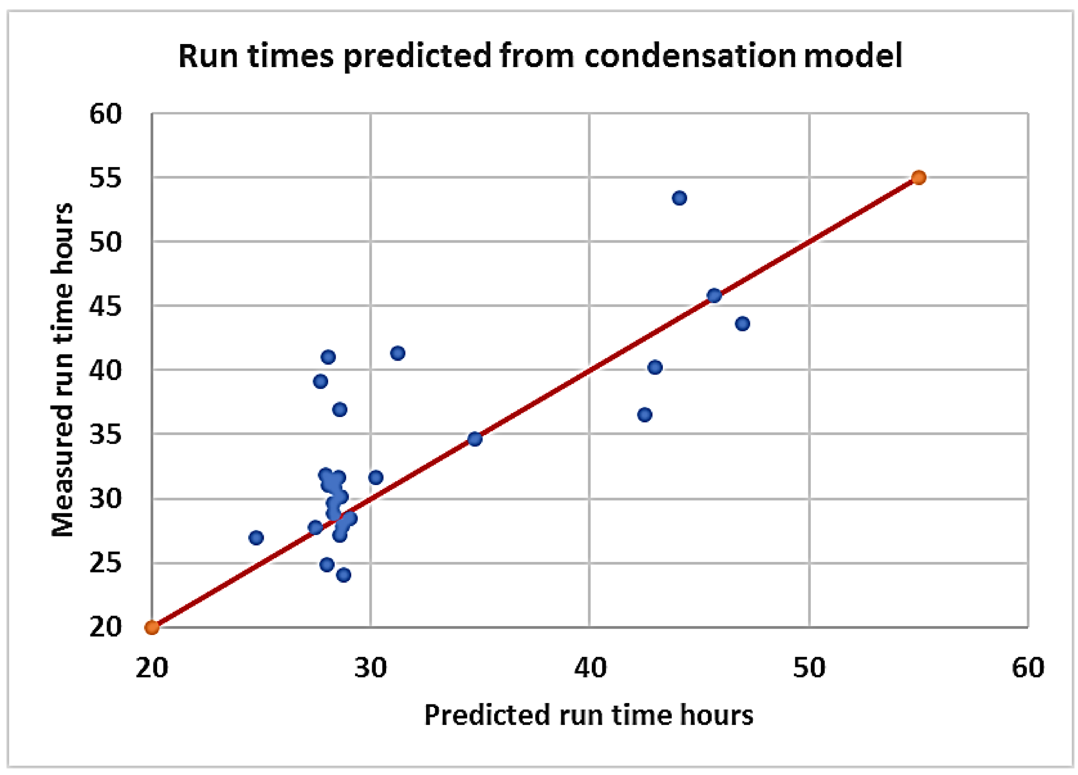


The modelled relationship corresponding to a total cooling power of 28 Joules and a 'base load' of 170µW is also plotted. The base load was estimated, from the average run time under no applied load, to be approximately 170µW.



If we assume the base load remains the same when the module is pre-cooled using a GM cooler, the additional cooling power available in a 'dry' system is expected to increase the unloaded run time to an average of ~56 hours, and the average 100µW-loaded run time to ~35 hours. These estimates are consistent with experimental data, both our own and as reported to us by end-users. Running the modules from a mechanical pre-cooler under automated control would also allow us to minimise the component of performance variability that is due to operational conditions, i.e. condensation temperature and pump temperature.

Using our simple condensation model to predict the run time for each individual module in each test run (right), the results suggest that the residual differences we observe in the performance of individual modules are primarily due to manufacturing issues. Potential sources of variability arising from manufacturing are a) the performance of the heat switch; b) the volume of ^{4}He in the module; and c) the size and finish of the superfluid-creep-preventing orifice. Of these three issues, the orifice size/finish quality and uniformity is the dominant factor, and is also the most difficult to further improve. We are working with Advanced Manufacturing Research partners on this challenge.



Developments in manufacturing technology have already led to big improvements in the average performance and reproducibility of ^{4}He sub-Kelvin modules. The quality of the superfluid-creep-preventing orifice remains a major focus of our ongoing R&D effort to produce low-cost, simple-to-use, reliable and reproducible sub-Kelvin ^{4}He modules for both academic and industrial users.