

A new ultra-low-temperature cryogen-free experimental platform

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Abstract. We report the introduction of a new cryogen-free dilution refrigerator experimental platform that provides significant performance enhancements, in several key areas, over the current generation of systems. In particular the ability to: install more experimental services; install higher-field experimental magnets; dissipate more power at the ~ 4 K stage; and to attain higher cooling powers and lower base-temperatures (below 3.5 mK) at the mixing chamber plate.

1. Introduction

The cryogen-free dilution refrigerator[1], often integrated with a superconducting magnet[2], has become the workhorse of many low-temperature laboratories around the world, and such systems are routinely used to attain temperatures below ~ 10 mK. In some fields of research, such as quantum information processing, these cryogen-free machines are preferred to “wet” systems using liquid ^4He as the installation of experimental services is more straightforward, for a discussion see[3].

There is now a drive from researchers in these fields for the ability to install more experimental hardware, particularly rigid coaxial microwave transmission lines and the associated signal conditioning elements (attenuators, circulators, bias-tees etc.) as well as the ability to run dissipative “cold” electronics at temperatures ~ 4 K. The heat loads from these experimental services need to be balanced carefully against the (limited) available cooling power from the mechanical refrigerators[4] used to generate the cold environment for these systems.

To facilitate the higher cooling powers required at 4 K we have developed a new experimental platform that is configurable with either one or two 1 or 1.5 W pulse tube coolers, that offers more access for the installation of services, and that can be integrated with large, high-field magnets. Optionally, this platform can be fitted with a powerful dilution refrigerator to enhance the cooling power available at lower temperatures. The design and performance of this platform shall be discussed in the following sections.

2. The experimental platform

The overall layout and principle of operation of this new system (single vacuum space, pre-cool circuit, Joule-Thomson condensing stage, automated operation etc.) is similar to smaller systems that have been described previously[2] and so here we focus on the enhancements this new platform offers.



2.1. Experimental access

The size of all the experimental plates have increased significantly. The mixing chamber plate on this platform is now 430 mm diameter and features 6×50 mm and 1×100 mm diameter line-of-sight ports to the system top plate.

The ~ 4 K plate (which determines the maximum dimensions of any magnet that can be integrated with the system) is 650 mm diameter.

The separations between the lower experimental plates have all been increased (to ~ 250 mm for the 4 K plate $\rightarrow$ still plate and cold-plate $\rightarrow$ mixing chamber plate, and to ~ 175 mm for the still plate $\rightarrow$ cold-plate) to provide more space to mount components, and to make fitting them more straightforward. Greater user access to the system is also facilitated by modifications to the support structure, as described in section 2.2.

The larger plates result in a longer cool down time than for smaller systems. The exact time from room temperature to base temperature will depend of the configuration of the pulse tube cooler(s) and the mass of any installed magnet, but is typically in the region of 50 hours for dual-cooler systems without magnets.

2.2. Support structure

The upper sections of the support structure (room-temperature $\rightarrow 70$ K and 70 K $\rightarrow 4$ K) are manufactured from stainless-steel tube and comprise three equally spaced straight legs. Between the 70 K plate and 4 K plate these tubes can be used to provide self-contained heat-pipes[5] to reduce the cool down time of large integrated magnets[6].

For the lower temperature stages MIL-I-24768/2 G10 tubes are preferred between the 4 K plate and the still, and carbon-fibre sections are used below the still.

This approach gives an open support structure, as shown in figure 1, which is mechanically very stiff and can support heavy experimental payloads (several hundred kg at the 4 K stage and several tens of kg at the mixing chamber) whilst also minimising its thermal conductivity. A discussion of the resulting heat load to the mixing chamber shall be given in section 4.2.

Whilst not yet measured, it is anticipated that the stiff support structure and more massive plates should result in vibration levels that are as good, if not better, than those measured on similar smaller systems of $< 0.1 \mu\text{m}^2 \text{ Hz}^{-1}$ from 0.1 Hz to 1 kHz.

3. 4 K stage cooling power

Pulse tube coolers are a source of mechanical vibration and are normally decoupled from the refrigerator plates using high thermal-conductivity, flexible copper-braids[2]. However, the conductivity of these braids is finite, so there is always some δT between the pulse tube stage and the plate.

Of interest to the experimentalist is the effective cooling power of the plate (to which their equipment is mounted) and the maximum dissipation permissible before the performance of the dilution refrigerator (and / or integrated magnet) is compromised. To quantify this a system with two Cryomech PT415-RM[7] pulse tube coolers, each of which is specified to have a second stage cooling power of 1.35 W at 4.2 K, was used. The temperature of both the pulse tube head and the experimental plate were determined using calibrated *cernox*[8] sensors and the power was supplied electrically *via* a resistive heater mounted near the centre of the plate. The results of these cooling power tests are summarised in figure 2. For the system described above, it was found that applying powers ~ 1 W had no measurable effect on the base temperature of the dilution refrigerator (which was below 6 mK) or the available cooling power at 100 mK. 2 W warmed the mixing chamber by around 2 mK. The operation of the integrated magnet will be discussed in section 3.1.

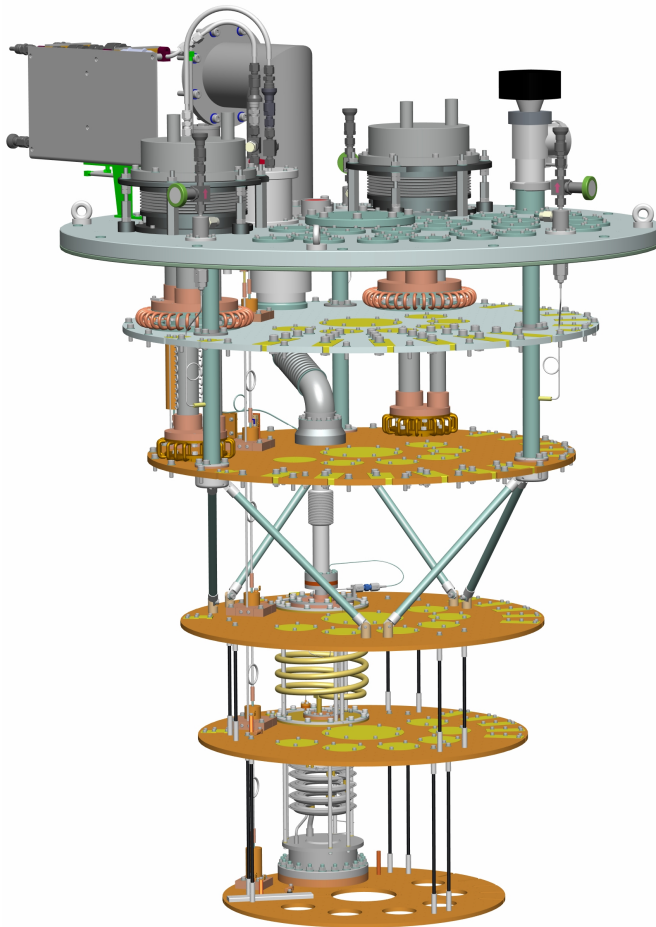


Figure 1. An image showing the general layout of the refrigerator with the vacuum and radiation shields removed. In this case the two pulse tube coolers can be seen at the top of the system and the large dilution unit at the bottom. For scale, the lowest plate (at the temperature of the mixing chamber) is 430 mm in diameter.

3.1. High-field magnets

Since the introduction of cryogen-free refrigerators with integrated superconducting magnets[2] there has been a push for ever higher fields at the sample position. Both the physical size and mass of a magnet increases rapidly as its design field goes up, meaning they can only be integrated onto a platform capable of supporting these heavy loads. The same is true for vector-rotation magnets (which allow the angle of the applied field with respect to the sample to be varied) as their formers become large to withstand the high forces between the coil sets as the fields become bigger.

The recent demonstration of the integration of nuclear demagnetisation stages with cryogen-free refrigerators to attain temperatures in the μK regime[9] has generated interest in providing a high-field experimental magnet (in addition to the demagnetisation stage magnet) in the same system.

The platform described in this article, with its larger size and upgraded support structure is suitable for all these applications.

A 16 T, 57 mm bore solenoid (which the authors believe to be the highest field magnet to be integrated with a cryogen-free refrigerator to date) that has a mass ~ 130 kg, an inductance ~ 60 H and an operating current ~ 140 A has been installed onto this refrigerator platform.

For systems requiring high cooling powers at the 4 K stage, magnets with higher critical-temperatures can also be manufactured. A wide bore (150 mm) 5 T magnet that can be ramped to full field at a temperature of > 5 K has been demonstrated. This means, that for the dual pulse tube system described in section 3, both the magnet and dilution refrigerator can operate

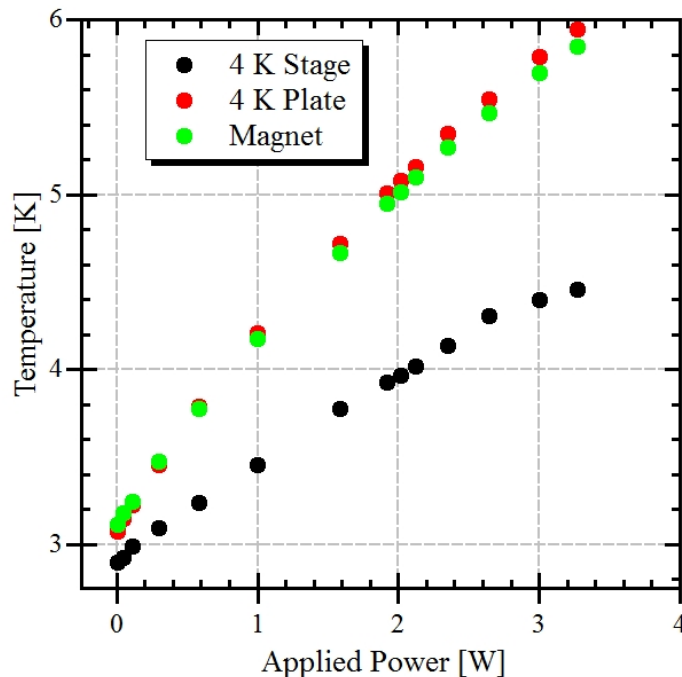


Figure 2. A graph showing the temperatures of the pulse tube cooler second stage, 4 K plate and magnet as a function of the power applied to the 4 K plate.

whilst a heat load ≈ 2 W is applied to the “4 K” plate.

4. High-performance dilution refrigerator

Dilution refrigerators with lower base temperatures and / or higher cooling powers at a given temperature are becoming a requirement for researchers working to develop general quantum computers. This is either because they hope their qubit will exploit a delicate quantum system that only manifests itself at extremely low temperatures[10], or (and) they hope to scale up to multiple qubit devices[11] and require higher cooling powers to overcome the additional dissipation per qubit whilst maintaining the system at a suitably low temperature.

The performance of a powerful dilution unit designed to be integrated with this new platform shall be described in the following sections.

4.1. Cooling Power

The cooling power of a dilution refrigerator at some elevated temperature (usually around 100 mK) is often chosen as a figure of merit. However it is not always appropriate to scale this performance to very much lower temperatures with simple relationships such as $\dot{Q} \propto T^2$ since the total heat load to the mixing chamber (including effects such as viscous heating) will be temperature dependant[12], as will be the optimal ^3He circulation rate.

The high-performance dilution unit designed for this experimental platform was characterised with a series of measurements. The cooling capacity was determined in vacuum, on the mixing chamber plate, as a function of temperature, figure 3. We find the cooling capacity at 100 mK is ≈ 1 mW, and is $> 25 \mu\text{W}$ at 20 mK.

4.2. Base temperature

The base temperature was determined with a commercial[13] noise thermometer[14] and verified using nuclear orientation[15]. Both thermometers were mounted in vacuum on the mixing chamber plate. The averaged temperature reported by the noise thermometer was

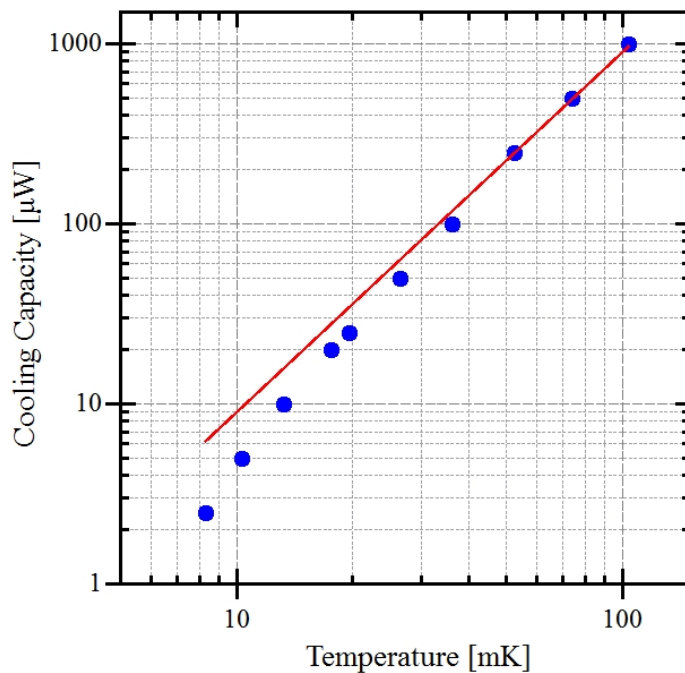


Figure 3. The cooling power available on the mixing chamber plate for a system equipped with the high-cooling power dilution refrigerator discussed in the main text. The 100 mK cooling power can be scaled as $\dot{Q} \propto T^2$ with reasonable accuracy at temperatures > 35 mK.

3.253 ± 0.016 mK (which the authors believe to be the lowest continuous temperature attained with a cryogen-free dilution refrigerator). From an analysis of the cooling power at low temperatures the total background heat load into the mixing chamber can be extracted. In this case we find a heat leak ≈ 240 nW.

References

- [1] Uhlig K 2002 *Cryogenics* **42** 73–77
- [2] Batey G, Buehler M, Cuthbert M, Foster T, Matthews A J, Teleberg G and Twin A 2009 *Cryogenics* **49** 727 – 734
- [3] Batey G, Chappell S, Cuthbert M, Erfani M, Matthews A J and Teleberg G 2014 *Cryogenics* **60** 24 – 32
- [4] Wang C and Gifford P E 2002 *AIP Conference Proceedings* **613** 641 – 648
- [5] Tien C L 1975 *Annual Review of Fluid Mechanics* **7** 167 – 185
- [6] Teleberg G, Matthews A J, Batey G and Elford J 2012 *Journal of Physics: Conference Series* **400** 052036
- [7] Cryomech: <http://www.cryomech.com/products/cryorefrigerators/pulse-tube/pt415/>
- [8] Lakeshore: <http://lakeshore.com/products/Cryogenic-Temperature-Sensors/Cernox/Models/>
- [9] Batey G, Casey A, Cuthbert M N, Matthews A J, Saunders J and Shibahara A 2013 *New Journal of Physics* **15** 113034
- [10] Das Sarma S, Freedman M and Nayak C 2005 *Phys. Rev. Lett.* **94**(16) 166802
- [11] Fowler A G, Mariani M, Martinis J M and Cleland A N 2012 *Phys. Rev. A* **86**(3) 032324
- [12] Pobell F 2007 *Matter and Methods at Low Temperatures* (Springer) 3rd ed
- [13] Magnicon: <http://www.magnicon.com/squid-systems/noise-thermometer/>
- [14] Casey A, Arnold F, Levitin L V, Lusher C P, Nyki J, Saunders J, Shibahara A, Vliet H, Yager B, Drung D, Schurig T, Batey G, Cuthbert M and Matthews A J 2014 *Journal of Low Temperature Physics* **175** 764–775
- [15] Marshak H 1983 *Journal of Research of the National Bureau of Standards* **88** 175 – 217

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