

Integration of superconducting magnets with cryogen-free dilution refrigerator systems

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ABSTRACT

There has been much recent research interest into “cryogen-free” dilution refrigerators. Cryogen-free systems have some advantages from a safety and convenience point of view as liquid cryogenics are unnecessary. However, this also makes integrating the low-temperature system with a high magnetic field environment much more challenging. Here we shall describe recent successes of integrating superconducting magnets and dilution refrigerators into one system requiring a single pulse tube cooler. The resulting environment provides experimental temperatures between 7 mK and 30 K and magnetic fields up to 12 T. We shall describe the effects of AC loss heating in such systems on the pulse tube refrigerator when the field is ramped and also the effects of eddy current heating on the mixing chamber in sweeping fields.

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1. Introduction

It was shortly after the theoretical prediction by London et al. [1] that a working helium-3/helium-4 ($^3\text{He}/^4\text{He}$) dilution refrigerator (DR) was constructed [2]. All early refrigerator systems used liquid helium to provide a cold environment and a separate pumped ^4He stage (the “1 K pot”) to condense the circulating ^3He .

It was noted that the requirement for the 1 K pot, and the associated pumps and gas handling system, could be removed by condensing the returning ^3He using a Joule–Thomson (J–T) heat exchanger [3]. In such systems the returning ^3He is only partially liquefied before heat exchanging with the still where all remaining gas is condensed: for a given circulation rate, this results in a slightly higher heat load on the still than in a system operating with a 1 K pot. This extra load on the still, coupled with the unavoidable parasitic heat loads conducted down the DR support structure, normally means that little or no extra electrical power need be applied to maintain a suitable ^3He circulation rate to operate the DR at base temperature. To maintain higher circulation rates then electrical power can, of course, be supplied in the normal way and in operation the cryogen-free DR behaves in a very similar fashion to a traditional refrigerator.

The realisation that liquid helium was not required for the liquefaction of ^3He in a DR naturally led to attempts to remove the need for liquid helium to provide the cold environment for

DRs. So called GM closed cycle coolers based on the work of Gifford and McMahon [4] were trialled initially and working fridges have been constructed [5]. This type of cooler does suffer from two significant drawbacks for system integration: vibration; and maintenance. GM coolers have a moving displacer at the cold end of the cooler. This gives rise to a relatively high level of mechanical vibration and so great care needs to be taken with the rest of the system design to prevent this noise impairing the performance of the DR [5]. The displacer also needs to be replaced periodically which means the cooler needs to be removed from the system – this is undesirable if a DR has been built up around the cooler.

More recently there have been developments in the performance of pulse tube refrigerators (PTRs) [6] which operate on similar thermodynamic principles to GM coolers but do not require a moving displacer. This greatly reduces the mechanical noise in these coolers; the acceleration noise may be two orders of magnitude smaller than a GM cooler with the same cooling capacity [7]. It also means that all routine maintenance is restricted to room temperature components. However the maximum cooling power available at low-temperatures in PTRs is limited: typical values would be 1 W at 4.2 K.

It has been noted that the finite losses in the regenerator material in PTRs allows heat to be absorbed along the length of the regenerator without impairing the performance of the cooler [8]. This regenerator inefficiency can be used to facilitate the condensation of helium using the PTR [9], and such ideas have been readily incorporated into DRs [10].

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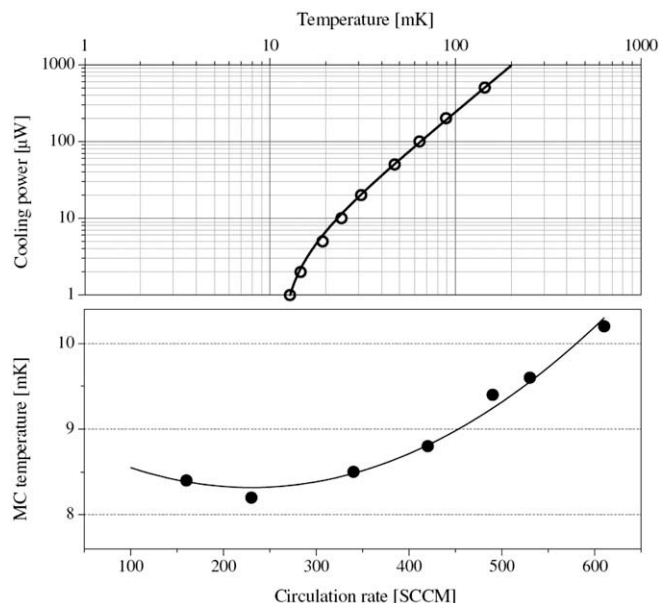


Fig. 2. Graph showing: Upper panel: The cooling power as a function of temperature for a standard (200 μW cooling power) dilution refrigerator. The open circles are data points and the curve through the points is the fit described in the main text. A cooling power of 240 μW at 100 mK was achieved. Lower panel: The base temperature of the same standard (10 mK base temperature) dilution refrigerator as a function of the circulation rate. The closed circles are data points and the curve through the points is the fit described in the main text. The base temperature was around 8.2 mK.

parameters determined by the fit. The condensing pressure of the returning ^3He varied from around 0.2 bar (absolute) at the lowest flow rates to around 0.55 bar at a flow rate sufficient to achieve to the 200 μW cooling power. These values are fairly typical of all the systems we have produced (nominal values would be 0.3–0.8 bar), but we note that these machines can operate comfortably with condenser pressures as high as 3 bar if necessary. The temperature of the PTR 2nd stage in this system was 2.4 K and this was independent of the circulation rate, demonstrating the effectiveness of the regenerator heat exchanger.

On higher cooling power machines, we have circulated ^3He at rates well above 1 mmol s^{-1} with the PTR still cooling to close to its unloaded base temperature (the maximum circulation rates being limited by the pumping system). The efficient pre-cooling of the ^3He is very important for systems with integrated magnets. This fact, combined with the high conductivity of the 2nd stage shield, allows the superconducting magnet to be maintained below a temperature of 5 K even when the mixing chamber is being controlled at temperatures as high as 30 K (more details of the magnet mounting and construction, and this high-temperature operation shall be given in later sections).

3. The pre-cooling system

A pre-cooling system has been developed, as depicted in Fig. 1, which uses the $^3\text{He}/^4\text{He}$ mixture to cool the dilution unit from room temperature, this greatly simplifies the system design and eliminates the need for a ‘traditional’ inner vacuum chamber (IVC), exchange gas and the associated tubes and leak tight (cold) joints. This pre-cooling concept also provides a very open structure for the installation of experimental services and means only a room temperature o-ring seal is required to access the cryostat.

The pre-cool loop operates by circulating the system mixture (using only the compressor pump) through a separate line which incorporates heat exchangers on the first and second stage of the

PTR: these heat exchangers are used to cool the incoming gas. This line then continues down to a heat exchanger at the mixing chamber (MC) of the DR via further heat exchangers at the still and cold-plate: these heat exchangers utilise the cold gas to cool the lower sections of the DR.

We have used the ^3He flow meter to measure approximately the flow of the $^3\text{He}/^4\text{He}$ mixture in the pre-cool line as a function of inlet pressure up to the maximum flow rate for which the meter is calibrated (just over 5000 SCCM). These data are summarised in Fig. 3. The fit in the figure is a simple power law of the form $F = \alpha P^\gamma$ where F is the flow and P the pressure. We find the exponent $\gamma \approx 1.7$.

Using this fit to extrapolate to higher pressures, we estimate that the initial flow in the pre-cool line at high temperature, where the PTR has a large cooling power, is around 25 standard litres per minute. This initial flow in the pre-cool loop does not effect the performance of the PTR unduly. As the PTR cools its cooling power is reduced and the flow in the pre-cool line is reduced correspondingly (fully automated sequences control the complete cool down and warm up process). Fortunately, the heat capacity of the material we wish to cool with the pre-cool loop also falls with temperature, so this reduction in the cooling power of the pre-cool loop with temperature results in a cooling rate at the MC that is fairly linear with time.

To estimate the available cooling power at the MC we have measured the minimum temperature achievable at the MC as a function of the flow in the pre-cool loop whilst a heat load of 0.25 W was applied to the MC plate. As the flow increases, so too will the load on the PTR 2nd stage which will cause it to warm, and so there should be an optimal flow rate to minimise the temperature at which a given cooling power can be achieved. The results of these measurements are shown in Fig. 4, from the figure it can be seen that a cooling power of 0.25 W can be achieved at a temperature of just below 13 K.

Although the cooling power of the pre-cool loop is significantly smaller than that available at the PTR this is not a problem in practice as the pre-cool loop is only used to cool the small mass of the DR below the level of the still. The magnet and radiation shields are coupled directly to the PTR (as will be described below) and for systems with magnets the cool down time is determined by the cooling of the magnet.

A DR system without a magnet will typically cool from room temperature to below 10 mK in approximately 18 h without using

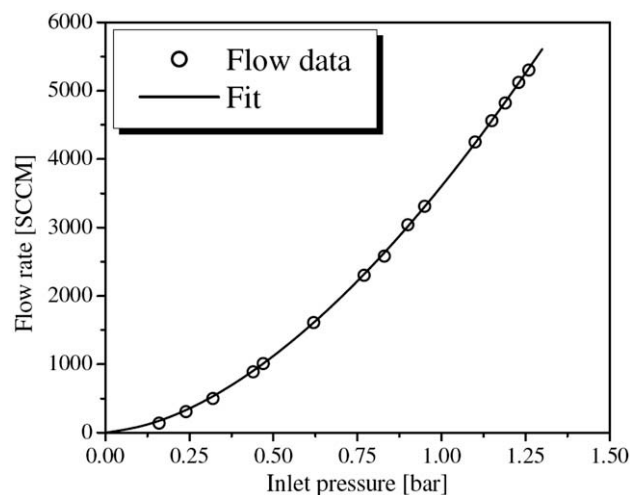


Fig. 3. Graph showing the flow rate through the pre-cool loop as a function of applied pressure. The open circles are data points and the curve through the points is the power law fit described in the main text.

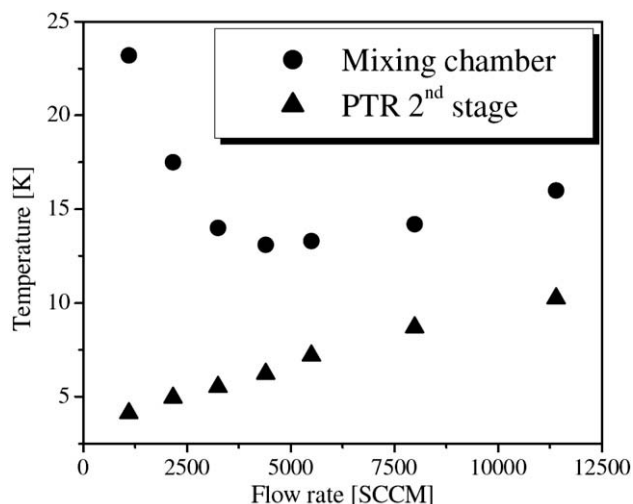


Fig. 4. Graph showing both the temperature of the mixing chamber plate and the pulse tube refrigerator 2nd stage as a function of flow rate in the pre-cool loop. A heat load of 0.25 W was applied to the mixing chamber plate throughout these measurements.

any other cryogenics. Cool down times with a magnet will depend on the specific details (mass, composition, coil arrangement, etc.) of the magnet. Fig. 5 shows the cool down from room temperature of an integrated DR and a 30 kg, 12 T magnet systems (using the Sumitomo PTR). The time for the DR to reach temperatures below 25 mK is approximately 33 h without using any other cryogenics.

4. Magnet and current lead design

The authors have successfully integrated 3, 5, 8 and 12 T magnets onto cryogen-free dilution refrigerators. In each case, the magnet was specifically designed for the cryogen-free environment and the heat loads from the magnet were balanced against those from the dilution refrigerator for quench-free operation.

The peak central field is dependent on both the temperature of the magnet and the peak magnetic field within the superconducting windings. If the magnetic field and temperature exceed the

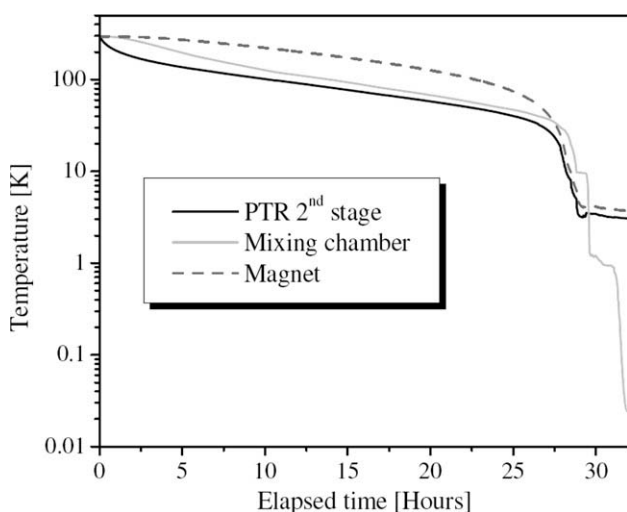


Fig. 5. Graph showing the cool down from room temperature of an integrated dilution refrigerator and 12 T magnet system cooling on a single 1 W pulse tube cooler. No cryogenics were used in this cool down. The mixing chamber of the system cools to below 25 mK in 33 h.

critical surface at which the superconductor becomes resistive, then the magnet will quench [20]. When operating an integrated cryogen-free magnet, the heat load on the PTR 2nd stage must be carefully matched to the load map of the PTR so that the additional heat load due to cooling and running the dilution refrigerator can be accommodated without the magnet warming to too close to its critical surface. The maximum field of an integrated magnet is set accordingly.

The magnet is mounted from a high purity, high-thermal-conductivity copper shield (Fig. 1) which is in good thermal contact with the 2nd stage of the PTR. The shields are arranged so that access to the sample region does not require complete removal of the still shield or magnet and nor does it require the unsoldering of the magnet leads.

Cryogen-free magnet construction relies on high conductivity, high purity copper links within the structure to extract heat efficiently out via the copper plate onto which the magnet coils are mounted. This copper plate is then bolted securely to the base of the PTR 2nd stage radiation shield. The shields are in turn attached to the second stage of the pulse tube by means of flexible links. Using this arrangement, the mixing chamber and magnet are both suspended from a single plate and are mechanically decoupled from the small displacements of the pulse tube [21]. This mounting arrangement also ensures motion of any sample (attached to the mixing chamber) with respect to the magnetic field is minimised – this is an important point to which we shall return later.

The integrated magnets have ranged in weight from 5 to 30 kg. The maximum stored energy to date being 86 kJ for the 12 T magnet. The cryostat and refrigerator components must be carefully designed to avoid damage to conductive components if the magnet windings become suddenly resistive and a large amount of energy is dissipated into the structure after a quench. Models and experiments were run to simulate quenches at the highest fields and the eddy currents in the cryostat structure resulted in forces well within safe limits.

The design of the magnet current leads is also critical when integrating a magnet and dilution refrigerator onto a single pulse tube. A modular design of current lead using high temperature superconductors (HTS) to reduce resistive losses below the PTR 1st stage has been adopted. In order to minimise the static heat load due to conduction down the resistive lead to the PTR 1st stage and down the resistive shunt and HTS tape to the PTR 2nd stage, HTS current leads for 40 A, 120 A and 240 A operation have been designed for specific magnets. In particular, the 240 A current leads require very efficient heat transfer to the PTR 1st stage due to the large resistive heating of the upper leads when in vacuum: although this heat load is not significant compared to the cooling power available at the PTR 1st stage, if it were not intercepted efficiently here it could contribute towards a significant heat load on the PTR 2nd stage. To ensure that there is efficient thermal contact to the PTR 1st stage plate a large surface area of copper is used in conjunction with an electrically insulating layer and flexible links.

The design of the magnet protection and persistent switch are also important. The protection for small superconducting magnets utilises diodes across the various magnet sections to minimise voltages in the event of a magnet quench. The use of diodes ensures the current supplied to the magnet gives a representative field with no time lag (due to the LR -time constant associated with charging the magnet). The cryogen-free superconducting switch is designed with a weak thermal link manufactured by thermally insulating the switch from the coil surface and providing a calculated quantity of copper rod (or wire) to optimise the time constant and heat load required to open the switch. This enables the user to run a magnet to field and hold the current at a set point in non-persistent mode whilst maintaining the temperature of the PTR 2nd stage at an acceptable level.

5. Magnetic field and heating effects

To the user of an integrated magnet system, the sample temperature when running the magnet is of paramount importance. To this end, we have deployed a commercial magnetic field fluctuation thermometer (MFFT) [22] to measure the mixing chamber temperature when running superconducting magnets. It is possible to use the MFFT in close proximity to a high field magnet due to the encapsulation of the device in an Nb cylinder which also reduces the parasitic noise. The MFFT was cross calibrated at high temperatures (100 mK) against a fully calibrated ruthenium-oxide resistive temperature sensor and the calibration was confirmed at low temperatures (<20 mK) by cross comparison with a nuclear orientation thermometer [23] both before and after the magnets were run.

An integrated 5 T magnet with a 77 mm bore was run to full field and back to zero field with a MFFT mounted on the mixing chamber plate (the MFFT experiences a peak field of 80 mT). The cobalt crystal used for the nuclear orientation temperature measurement was mounted adjacent to the noise thermometer at the centre of the mixing chamber plate.

The temperatures recorded at the magnet plate and the mixing chamber plate ramping up and down to 5 T at 0.31 T/min are shown in Fig. 6. The magnet ramp starts at 0.5 h: prior to this, the switch heater was energised at 22 mA (resistance $\approx 105 \Omega$) and the corresponding temperature rise of the magnet (and hence PTR 2nd stage) is clearly seen (in the upper trace). The first peak in temperature (3.77 K) occurs shortly after the magnet ramp starts due to the higher AC losses at low field [20]. The magnet does not reach peak field until 0.75 h, after which the temperature drops rapidly from 3.68 K to maintain a steady state temperature trending to 3.52 K. The 0.35 K offset in the temperature of the magnet, and therefore the PTR 2nd stage, is entirely due to the constant power supplied to hold the superconducting switch open whilst the magnet is at peak field. The magnet temperature increases to 3.85 K when subsequently ramping the magnet down. This occurs after the highest AC losses which occur close to zero field. The current to the magnet switch is removed at 3¼ h and the base temperature of the magnet plate returns to 3.18 K. Throughout the energization process, the magnet temperature does not exceed 4 K. It is also clear from the figure that there is no evidence of Joule

heating at the PTR 2nd stage as the magnet is energised, confirming the suitability of the HTS leads for these systems. We also see no evidence of heating at the PTR 1st stage (this is true for all of the systems tested – the PTR 1st stage typically sits below 50 K).

The lower trace shows the mixing chamber temperature when running the magnet. The time constants associated with the heat generated due to eddy currents in the components at ultra-low temperatures are clearly longer than those at 4 K. The mixing chamber takes around 1 h to return to less than 10 mK (no adjustment was made to the still power to increase the ^3He circulation rate, and hence the cooling power of the DR, during or after the magnet sweep).

The effect on the mixing chamber temperature of ramping the magnet at different rates was subsequently studied and data for different ramp rates are shown in Fig. 7.

When ramping up the magnet at 0.31 T/min, the base temperature rises from 7.6 mK to peak at 40 mK. The peak occurs when the magnet reaches full field. The corresponding peak temperature when ramping more slowly at 0.155 T/min was lower (24 mK). Following both the slow and fast ramps, the mixing chamber temperature trends back to close to the initial base temperature after approximately ¾ h. Comparison of the in-field and zero-field cool down curves shows that there appears to be a small offset in the base temperature when the system cools in-field. However, during measurements on higher field systems we found that the MFFT is unable to operate in applied fields above 85 mT, and so the slight offset in the measured temperature, and the larger uncertainty in the temperature measurements are attributed to the initial stages of flux penetration into the MFFT device at 80 mT.

We note here that we have seen no evidence for any significant extra heat load on the MC when any of the magnet systems we have produced to date have been held at a constant field – this is true for systems incorporating PTRs both with and without remote motors. Such heating could occur if there were eddy currents induced in the DR structure due to any relative motion of DR and magnet. The absence of such heating effects demonstrates the success of the design methodology used for supporting the magnet and decoupling the cold heads of the PTR as described above.

Our integrated 12 T magnet with a 57 mm bore is, to the authors' knowledge, the highest field solenoid to be integrated onto a cryogen-free dilution refrigerator to date. The temperature

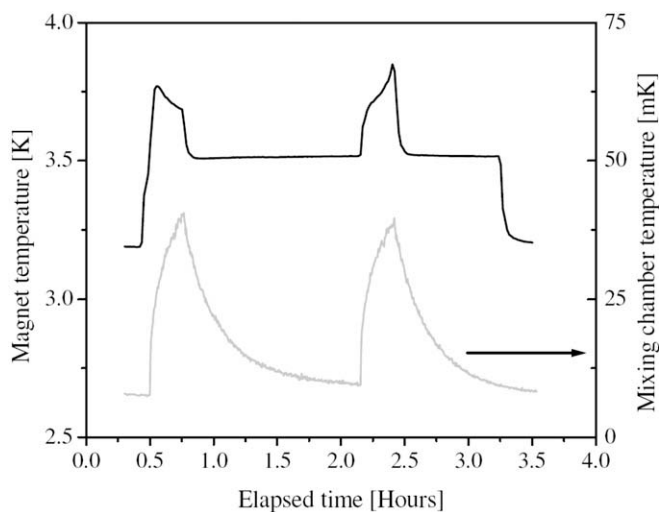


Fig. 6. Graph showing the temperatures of the magnet and mixing chamber throughout a magnet sweep to full field (5 T) and back to zero field. The features of the graph are explained in detail in the main text.

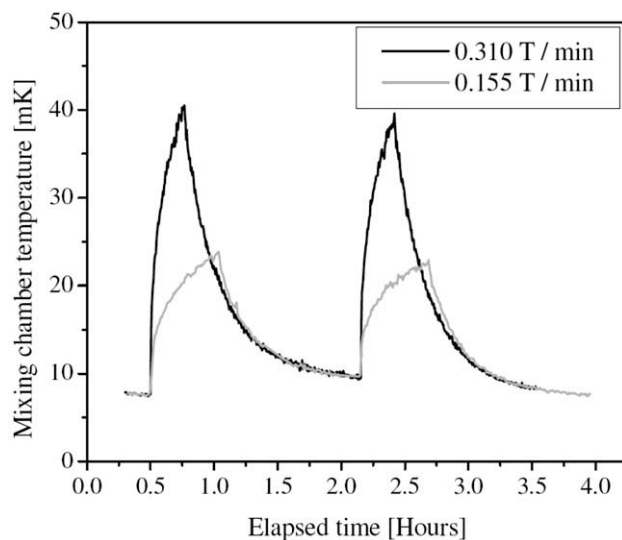


Fig. 7. Graph showing the mixing chamber temperature as the magnet is swept at different ramp rates to full field (5 T) and back to zero field. The features of the graph are explained in detail in the main text.

measured at the PTR 2nd stage, the magnet and the mixing chamber when cooling the system down from room temperature is given in Fig. 5. The magnet cools in less than 30 h. The interaction of the DR with the magnet and pulse tube temperatures is clearly seen when circulation of the mixture begins. The mixing chamber subsequently cools to less than 25 mK (the limit of the calibration of the RuO₂ sensor) in less than 33 h. A base temperature of 8.2 mK was recorded using NO thermometry within 36 h of the start of the cool down.

6. Temperature control

The combination of the dilution unit pre-cool facility and the design of the ³He to PTR heat exchangers makes it very convenient to operate the cryogen-free dilution refrigerator over a very broad range of temperatures (<10 mK to >30 K) while still being able to operate a superconducting magnet.

The dilution unit pre-cool line enables the mixing chamber to be cooled rapidly from 'high' temperatures without having to introduce and then pump exchange gas to cool the unit. Fig. 8 demonstrates the effectiveness of the pre-cool line when returning the system to lower temperatures after high-temperature operation. As can be seen in the figure, starting the pre-cool loop increases the cool down rate of the DR MC by approximately a factor of 20.

We note here that although some workers favour a system design featuring an IVC and the use of hydrogen exchange gas (which "freezes out" and hence does not necessarily require the pumping of the IVC when cold) we prefer not to employ this approach for the following reasons: safety; the requirement for an IVC, the associated cold joints and complications when adding experimental services; the possibility of small time dependant heat leaks arising from the ortho-para conversion of hydrogen after it has condensed; and the likelihood that stable temperature control above 20 K would be very difficult to achieve.

The design of the pre-cool line heat exchangers allows control of the mixing chamber over this extended temperature range whilst maintaining a sufficiently low superconducting magnet temperature (less than 5 K) such that the magnet can be operated over the full field range. Careful consideration of the thermal links to the PTR 2nd stage enables this magnet temperature to be maintained even when the combined heat loads of sweeping the field

and operating the DR in the 'high' temperature operation mode are imposed.

The temperature control results for a cryogen-free dilution refrigerator with an integrated 12 T magnet are presented below. All temperatures quoted were measured on the mixing chamber mounting plate using one of three temperature sensors: a generically calibrated ruthenium oxide sensor (a standard Oxford Instruments type M0 temperature sensor), a fully calibrated cernox sensor [24] and the MFFT device. Temperature controls were carried out using a Lakeshore 370 AC resistance bridge [24] to monitor the control sensor and provide power to a resistive heater mounted on the mixing chamber plate. The system was fitted with a low eddy-current sample holder in order to mimic the likely conditions during a 'real' experimental run as closely as possible (such as the extra heat load to the system due to eddy current heating). The low eddy-current sample holder was screwed into the mixing chamber mounting plate and extended down to the field centre line position ending in a flat copper sample mounting area 10 mm long by 6 mm wide.

The inherent base temperature stability of the system (i.e. without an active temperature control feedback loop) was monitored using the MFFT thermometer with a measurement interval of 30 s. The base temperature, at zero magnetic field, measured over a period of approximately 1.5 h can be seen in Fig. 9. The temperature was measured to be 8.3 ± 0.2 mK (mean $\pm$ standard deviation). Also shown in Fig. 9 is the measured mixing chamber temperature whilst controlling the temperature at 30 K and simultaneously ramping the magnet from zero field to 12 T and back to zero at 0.3 T/min. The standard deviation of the temperature measurements was 3.5 mK and the maximum deviations were approximately ± 7 mK. The magneto-resistance effects of the cernox control sensor (which we did not attempt to compensate for) are likely to amount to <20 mK over this temperature and field range [24].

Unfortunately we are unable to show any data for the base temperature of the DR when the 12 T magnet is at fully energised. The MFFT is unable to operate in this level of stray field. Resistance thermometry is notoriously difficult to operate reliably at these temperatures (<10 mK) and the magneto-resistance of the ruthenium oxide sensors can be large ($\Delta T/T \approx 20\%$) as well as being temperature and field dependent [25], hence we have not attempted to correct for these effects. It is possible to use either a

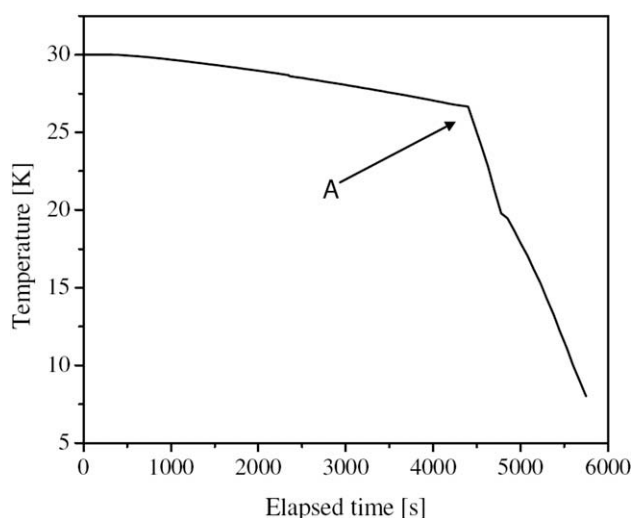


Fig. 8. Graph showing the cool down of the mixing chamber after temperature controlling at 30 K. The very slow initial cooling is without the pre-cool line. The sudden increase in the cooling rate, at the point indicated 'A', is due to the pre-cool line being started.

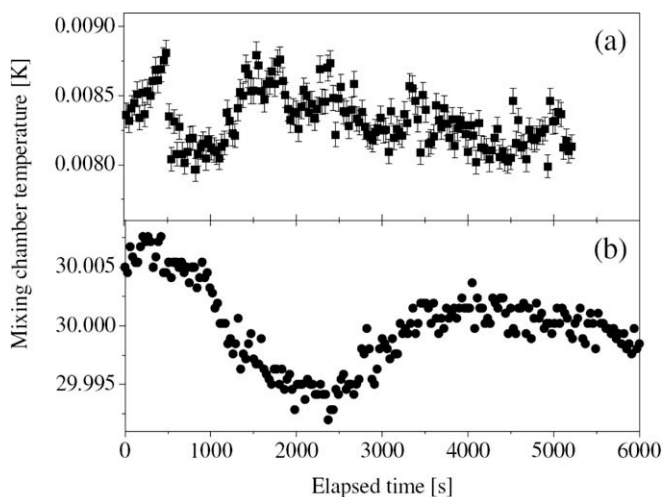


Fig. 9. Graph showing (a) the base temperature, at zero magnetic field, measured with the magnetic field fluctuation thermometer on the integrated 12 T magnet system with no closed loop control, and (b) the temperature of the mixing chamber as it is closed-loop controlled at 30 K whilst the magnet is swept to full field and back to zero field at 0.3 T/min.

Coulomb blockage thermometer [26] or single junction thermometer [27] in magnetic fields, but it is not clear that these devices are yet suitable for measurements down to the low millikelvin temperature range.

In separate experiments we have also found that by over biasing the control sensor, and accepting a small level of sensor self heating (~ 2 mK at 20 mK), the closed loop control of the system can be improved. In the temperature range 20–300 mK control to better than 10 μ K has been achieved.

7. Experimental services

The open structure of the cryogen-free DR system enables a wide range of experimental services to be installed in a straightforward manner, as demonstrated in Fig. 10.

However, in contrast to traditional systems using liquid cryogenics, the heat loads from additional services at the high temperature (300–4 K) portions of the system are also of critical importance. Whereas traditionally the 4.2 K stage of a cryostat would always sit at that temperature and an increased heat load would simply result in increased cryogen consumption, in cryogen-free systems there is a finite amount of cooling power available at the PTR 1st and 2nd stages. Increased heat loads mean these stages warm to higher temperatures, where the PTR has more cooling power. This is much less of a problem for the DR than for the magnet and means that the heat load from all experimental services should be considered carefully at the design stage. In general there will be several hundreds of mW of cooling power available at the PTR 2nd stage for experimental services and so this restriction is not too severe in practice.

The example pictured in Fig. 10 shows a system with: 10 off flexible coaxial cables (suitable for signal frequencies

~ 500 MHz); 10 off semi-rigid coaxial cables (suitable for frequencies ~ 18 GHz, in this case limited by the choice of connectors on the coaxial cables, operation to 40 GHz is possible with alternative connectors); 96 DC leads as twisted pairs (both normal conductors and superconducting); and 2 off optical fibres (one single mode and one multi-mode) all fitted from the room temperature top plate down to the mixing chamber.

The open structure of the system also means that there is ample space for effective thermal dumping of these services at lower temperatures: a base temperature of 8 mK was recorded with all the above experimental wiring installed; and 10 mK with the experimental wiring plus the optical fibres. The thermal dumping of the wires is achieved by clamping the leads on each of the DR support plates. This provides breaks at approximately 50 K, 4 K, 0.7 K and 100 mK before the wiring arrives at the MC and keeps the conducted heat loads through the wiring to an acceptable level. As the optical fibres are extremely delicate these were not clamped and instead their intrinsically low thermal conductivity was relied upon and they were run directly to the MC.

Commercially available attenuators [28] can be fitted to the semi-rigid coaxial cables at each thermal break if desired and depending on the optimum experimental requirements for thermal performance and electrical transmission properties, cables with stainless steel inner and outer conductors or similar arrangements using BeCu and/or Nb conductors can be employed.

Optical windows can very conveniently be fitted through the system as the single vacuum space means that only a room temperature seal is required to make the system leak tight. Elimination of the requirement for exchange gas during cool down also means that there is no longer a concern over a helium film in the optical path compared to an equivalent 'wet' system.

The total absence of helium in the sample region below the mixing chamber also makes these cryogen-free systems particu-

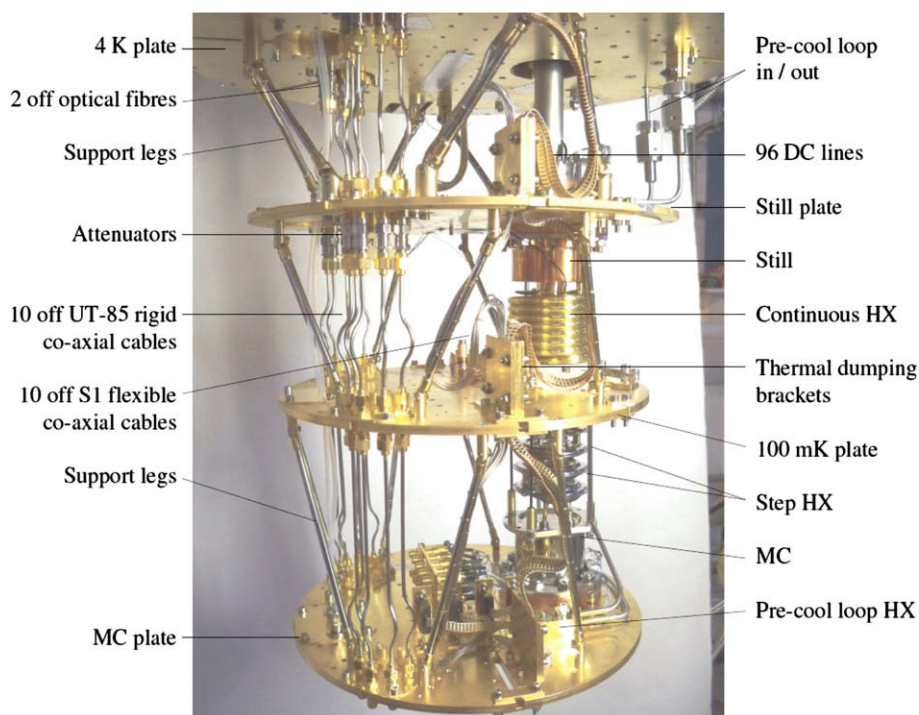


Fig. 10. Photograph showing the lower portion of a cryogen-free dilution refrigerator, the main components are labelled, the mixing chamber is abbreviated MC and heat exchangers as HX. Also shown are some of the possible experimental services that can be mounted onto a cryogen-free dilution refrigerator. Even with the extra heat load from all of these services, the base temperature of the machine was measured to be 10 mK.

larly well suited to neutron scattering experiments, and thin, high-purity Al tail sets have been constructed for this application.

For some applications it would also be convenient to be able to tilt the cryostat. We have demonstrated that the entire standard DR assembly can be tilted by at least $\pm 35^\circ$ and still operate, without impairing significantly the DR performance.

8. Conclusions

We have engineered several integrated dilution refrigerator and cryogen-free, high-field magnet systems and found that the experimental conditions in terms of: temperature range; temperature stability; eddy current heating; and cool down time all look extremely favourable. Temperatures less than 10 mK in fields of 12 T are achievable and cooling powers of $>400 \mu\text{W}$ at 100 mK are available. Temperature control spanning four decades has also been demonstrated. The superconducting magnets remain operational to full field whilst the mixing chamber is controlled at temperatures up to 30 K. Cool down times of less than 36 h are possible with a 12 T magnet and dilution refrigerator mounted from a single pulse tube cooler, and less than 18 h for a dilution refrigerator without a magnet. The installation of experimental services is also extremely convenient compared to its 'wet' counterpart.

We therefore conclude that with the advent of 'dry' integrated systems the interest in, and adoption of, this technology is likely to increase dramatically over the next few years.

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