Millikelvin cryocooler for space and ground based detector systems

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ABSTRACT

This paper describes the design of a continuously operating millikelvin cryocooler (mKCC) and its origins. It takes heritage from the double adiabatic demagnetization refrigerator (dADR) which was built for the European Space Agency (ESA). The compact design is based on a tandem configuration continuous ADR which alternately cycles two dADRs. The mKCC is a single module (dimensions 355 x 56 x120 mm) which operates from a 4 K bath (liquid or cryocooler) and provides an interface to the user which is settable from < 100 mK to 4 K. Predicted maximum cooling power at 100 mK is 7μW. It will use only single crystal tungsten magnetoresistive heat switches (the first ADR cooler to do so) and the measured thermal performance of these heat switches is presented. The mKCC uses ten shielded 2 Tesla superconducting magnets capable of ramping to full field in 20 – 30 seconds. This has been demonstrated in the lab and the results are given for the successful performance of a prototype Chromium Potassium Alum (CPA) pill using one of these magnets. The mKCC has been designed to be fully automated and user friendly with the aim of expanding the use of millikelvin cryogenics and providing a good testing and operating platform for detector systems.

Keywords: Millikelvin cryocooler, Adiabatic Demagnetization Refrigerator, Magnetoresistive heat switch, Continuous cooling, Tungsten.

1. INTRODUCTION

Adiabatic Demagnetization Refrigerators (ADRs) have been used and developed at MSSL for over 20 years. Our research has been driven by the need for detectors in both space and ground based systems to be cooled down to millikelvin temperatures. We use the latest technology and push technological limits with the goal to minimize mass, reduce operating temperature and increase cooling power. We developed and in 2008 successfully delivered to the European Space Agency (ESA) an Engineering Model (flight qualified) double ADR. Based on this heritage, and from the development of the tungsten magnetoresistive heat switch, we are currently developing a cryocooler module which can be coupled to a mechanical 4 K cryocooler and provide continuous cooling from sub 100 mK to 4 K.

1.1 Adiabatic Demagnetization Refrigerator theory

ADRs use the process of magnetic cooling to reach millikelvin temperatures. Magnetic cooling was first proposed by Debye (1926)[1] and independently by Giauque (1927)[2] and was first demonstrated by De Haas, Wiersma and Kramers[3] in 1933, Giauque and MacDougall[4] in 1933 and by Kurti and Simon[5] in 1934. Cooling is achieved by reducing and controlling the entropy of a paramagnetic material. More specifically, the alignment of the electronic dipole moments of magnetic ions within the material is controlled by use of a magnetic field. The ideal process of magnetic cooling involves: 1) a magnetic field being applied and the dipole moments aligning with the field (reducing the entropy of the paramagnet). In the ideal case magnetization is isothermal and therefore the magnetization energy produced Q_m is equal to TdS; 2) the paramagnetic material then being thermally isolated from its surroundings; 3) the magnetic field being reduced, resulting in cooling. Figure 1 illustrates the ideal process of magnetic cooling and shows how the entropy and temperature of the paramagnetic material vary with magnetic field.

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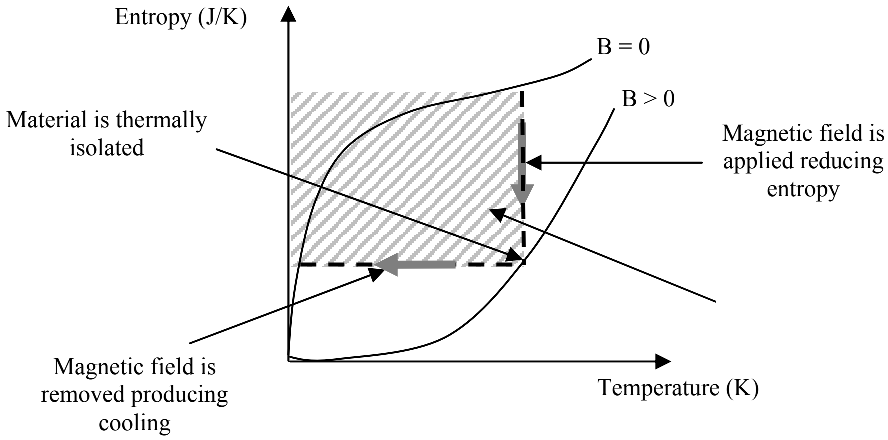

Figure 1: Variation of entropy and temperature of a paramagnetic material during the ideal process of magnetic cooling.

ADRs have three main components: a paramagnetic material, a magnet and a heat switch. The paramagnetic material is suspended within the bore of the magnet via low thermal conductivity supports and is connected to the heat bath (typically 4 K) via the heat switch. In addition there is a mechanical interface to the pill upon which the samples/detectors to be cooled are mounted (commonly referred to as the cold finger). A schematic of a single ADR is shown in Figure 2.

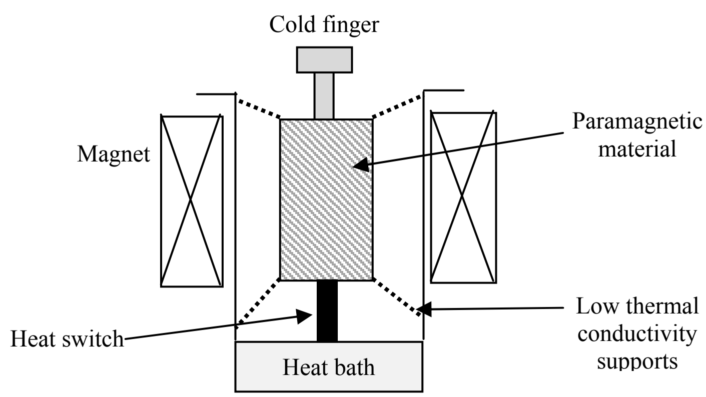

Figure 2: Single ADR schematic.

Operation of the ADR is based on the ideal process of magnetic cooling as described above but real world limitations mean that magnetization is not isothermal (this is limited by the thermal conduction of the heat switch) and demagnetization is not fully adiabatic (the paramagnetic has to be physically suspended and the low thermal conductivity supports lead to a very small heat leak as well as the heat capacity of the sample/detector being cooled). The operational procedure for the ADR is thus as follows: 1) magnetization of the paramagnetic with the heat switch closed so that the magnetization energy is extracted to the bath; 2) a cooling period during which the paramagnetic is allowed to cool to the bath temperature via the heat switch; 3) Isolation of the paramagnetic from the bath (by opening the heat switch) followed by demagnetization. After an ADR has been fully demagnetized, the paramagnetic material will start to warm as it absorbs the parasitic heat loads from its surroundings and the item it is cooling. However many users will need a stable operating temperature for the instrument they are operating. This can be achieved by either: 1) fully demagnetizing the ADR and then using a heater to provide a stable temperature by decreasing the heater power over time or 2) partially demagnetizing the ADR to the required operating temperature and then demagnetizing further but at a rate so as to counteract the heat flow into the pill due to parasitic heat loads from other parts of the ADR and from the experiment. This can be achieved manually or by the use of an automated computer control program. Of the two methods, that of partial demagnetization is favoured as it is the most thermally efficient. The total amount of energy Q_a which can be

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absorbed by the paramagnetic whilst at the required operating temperature (often referred to as the hold temperature T_h) is given by $T_h(S_f-S_i)$ which is depicted by the grey shaded area in Figure 3.

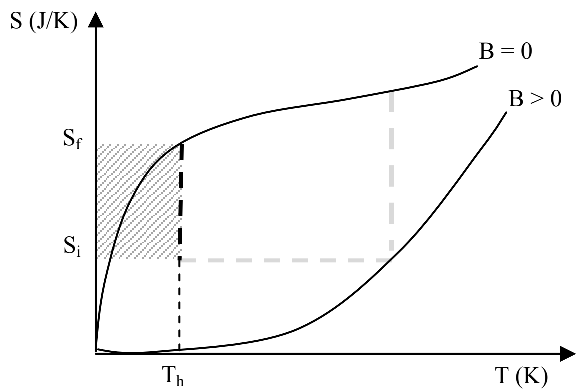

Figure 3: Total energy that can be absorbed by a paramagnetic material at hold temperature T_h.

The duration for which the paramagnetic can be held at the operating temperature is referred to as the hold time t_h which is equal to the total energy that can be absorbed Q_a divided by the total heat load (power) applied to the paramagnetic due to the parasitic heat loads plus the heat load from the instrument/detector.

1.2 ADR configurations

The most basic ADR configuration is that of the single ADR (shown in Figure 2) but this can be relatively limited in performance in terms of cooling power and/or hold time. To improve performance, multiple paramagnetic stages can be used. There are two different types, a two-stage ADR and a double ADR (dADR) which differ in the number of magnets used and the way they recycle. A two stage ADR (Figure 4) uses the second paramagnetic material as a heat buffer to reduce the parasitic heat load onto the low temperature stage. This allows for a longer hold time and/or greater cooling power. Each pill is connected to the heat bath via a heat switch and both pills are controlled with the same magnet i.e. they are magnetized and demagnetized in parallel.

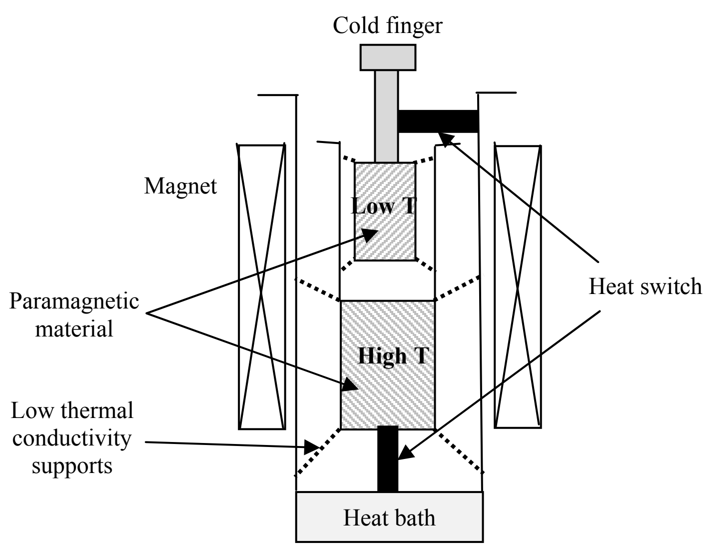

Figure 4: Two-stage ADR schematic.

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A double ADR (Figure 5) commonly uses two different paramagnetic materials, a high temperature material which is connected to the heat bath via a heat switch and a low temperature material which is connected to the high temperature stage via a heat switch. Unlike the two stage ADR, the pills each have their own magnet and are demagnetized in series rather than in parallel; the high temperature stage is demagnetized whilst in good thermal contact with the low temperature stage so that the low temperature stage is pre-cooled (typically to 1-2 K). This allows the low temperature stage to have a much lower demagnetization starting temperature and entropy resulting in a longer hold time and/or greater cooling power than a single or two stage ADR. In this configuration, the high temperature stage can be replaced by a helium-3 sorption cooler but the sorption cooler has the disadvantage of requiring a 2 K heat bath whereas paramagnetic materials can easily be operated from 4 K. It should be noted that although only two paramagnetic stages have been shown, ADRs can use many stages in order to operate from a higher bath temperature or to reduce the strength of the magnetic fields used by having a smaller temperature difference across the stages.

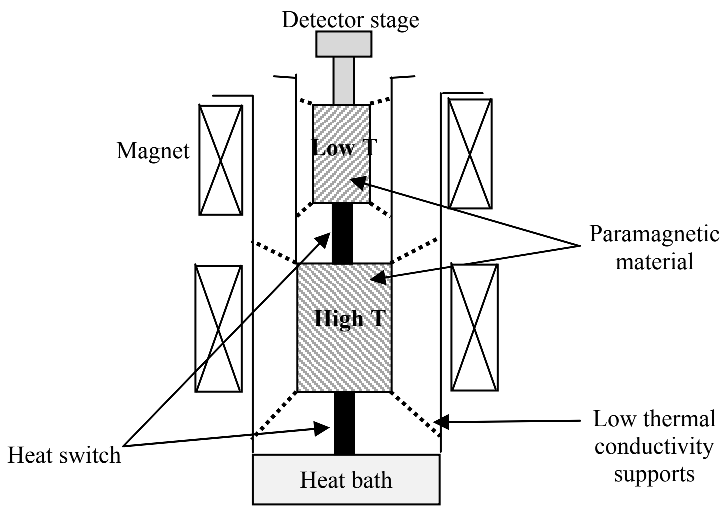

Figure 5: dADR schematic.

The main drawback with ADRs is that they can only achieve very low temperatures for a limited time. Once fully demagnetized the system will start to warm up and therefore the recycling process of magnetizing and demagnetizing will need to be completed once again to return to the required operating temperature. This is not always ideal as it will result in periods when the ADR is too warm for the detector or experiment to operate which corresponds to dead time. When long operating periods are required this could lead to very large systems (so a large total heat load can be accommodated) and when millikelvin cooling is required for several weeks and months this is impractical. A solution to this is the Continuous ADR (CADR) which can provide continuous cooling at millikelvin temperatures by operating two dADRs in a tandem configuration; both dADRs are connected via a heat switch to a continuous millikelvin stage and whilst one is recycled (with the heat switch in the off state) the other dADR is cold and controlling (holding) the millikelvin stage at the operating temperature via a heat switch in the ‘on’ state. Once the recycling dADR has completed recycling and reached the operating temperature, it will be connected to the continuous stage (the heat switch will be turned on) and will take over the temperature control. The other dADR will be disconnected from the continuous stage (the heat switch will be turned off) and will begin recycling. This is the basis of the millikelvin cryocooler.

1.3 The ESA ADR

MSSL first proposed a multistage ADR in 1995 (Hepburn et. al[6]), and started developing the first dADR for space for the European Space Agency, ESA in 2002. This ADR is known as the ESA ADR and was successfully delivered to ESA (although it remains at MSSL as a test bed) in 2008. The ESA ADR is an engineering model (EM) dADR which was designed and built for the former ESA mission XEUS (X-ray Evolving Universe Spectroscopy mission) which later became a joint ESA-NASA-JAXA mission named IXO (International X-ray Observatory) and which has since become

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the ESA mission Athena. The main driving requirements were: 1) a cold finger temperature of 50 mK (with a target of 30 mK) for 24 hours with a 1 microwatt heat load and with a 4 hour ADR recycle time; 2) A maximum heat load to the ADR heat sink of < 5 mW in order to allow cooling via a space cryocooler; 3) A magnetically shielded < 5 μT (0.05 Gauss) detector focal plane (even when the magnets are at full field of 3 T) to house superconducting tunnel junction (STJ) or transition edge (TES) x-ray detector arrays and associated SQUID readout electronics; 4) Magnetic screening of the whole system to reduce the exported stray magnetic flux density to a level acceptable to a spacecraft (< 67 μT, < 0.67 Gauss) at a distance of 50 cm from the centre of the dADR. A brief design and performance summary is given below. (Refer to Bartlett et al.[7] for a detailed description of the design and performance).

The ESA ADR is designed to operate from a 4 K bath which is provided by a pulse tube refrigerator (PTR) for ground based testing but which would be provided by a 4 K Joule-Thompson cooler in space[8].Two different paramagnetic materials are used; for the high temperature stage, 0.9 mol of single crystal Dysprosium Gallium Garnet (DGG) is used which has a diameter of 57 mm and a height of 96 mm and is the largest single crystal of DGG in the world; for the low temperature stage, 0.56 mol of Chromium Potassium Alum (CPA) which is a compressed pill (ground CPA crystals are compressed onto a gold plated copper thermal bus) and has a diameter of 40 mm and a height of 166 mm. The DGG operates from 4 K to 0.6 K and the CPA from 1.6 K to 25 mK and both materials are suspended within the magnet bore by the use of a Kevlar suspension system using Belleville springs. The DGG is connected to the 4 K bath via an active gas-gap heat switch[9] and to the CPA via a superconducting lead heat switch comprising of lead wire wrapped around a low thermally conducting Vespel™ SP22 rod. The magnet system has two sections – one for each paramagnetic material. Each section consists of a main coil, two field compensation coils situated at the end of the main coil to boost the end field and two stray magnetic field control coils which reduce the stray magnetic field to the required levels. The central magnetic field flux density of 3 Tesla is generated using ≤2.4 A. The total mass of the ESA ADR including magnetic shielding is approximately 45 kg and about 32 kg excluding the magnetic shielding.

At the time of delivery in July 2008 the EM ADR had the following performance: a recycle time of 15 hours, a hold time at 50 mK (with an average parasitic heat load of 2.34 microwatts) of 10 hours, a base temperature of 25 mK and a measured temperature stability of ±8 μK. The cryostat had been maintained at 4 K for 13 months in order to enable regular operation of the dADR in order to ascertain reliability. Over this period the dADR performance did not degrade showing excellent reliability. The ESA ADR was a fully automated system and on many occasions was remotely operated via the internet.

From extensive mathematical modelling of the performance of the ESA ADR (with the model being proven to be in excellent agreement with the experimental results) it was determined that the performance of the ADR was limited somewhat by thermal boundary resistance within the CPA pill but mainly due to the thermal performance of the superconducting lead heat switch which lead to a much longer recycle time than the required 4 hours (due to its low 'on' thermal conductivity) and a shorter hold time than the required 24 hours (due to its high 'off' thermal conductivity).

This is a large ADR system which is now too heavy for more modern requirements. It is also limited by being a single shot system resulting in down-time in the operation of the detectors mounted on the focal plane. Since delivery of the ESA ADR, a new heat switch has been developed at MSSL which would enable the ESA ADR to meet and exceed the design requirements (the predicted recycle and 50 mK hold time are 2 and 29 hours respectively) by replacing the existing superconducting lead and gas-gap heat switches. This switch, the single crystal tungsten magnetoresistive heat switch is discussed in the next section.

2. TUNGSTEN MAGNETORESISTIVE (MR) HEAT SWITCH

Development of a single crystal tungsten MR heat switch has been ongoing at MSSL since 2005. These heat switches are of great interest due to the very high switching ratios (potentially 100,000 at 4 K) [10] that can be achieved over a large temperature range (> 4 K to mK) which is crucial to the development of the millikelvin cryocooler (see section 3). In addition to having fast switchover times between the on and off states (this is only limited by the magnet ramp time) compared to a gas-gap heat switch, it is also tunable i.e. as the magnetic field is varied the thermal conductivity is varied so there is no sharp transition between on and off.

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2.1 MR theory

In metals, heat is conducted by electrons and phonons with the former being the dominant process. In magnetoresistive materials, which are compensated metals with closed Fermi surfaces, electronic conduction can be suppressed by the application of a magnetic field in a direction perpendicular to that of the electron flow, with the heat conducted due to electrons decreasing with increasing magnetic field. This can ultimately result in the thermal conductivity being dominated by phonons. Switching is therefore achieved by the application and removal of an external magnetic field; the 'on' highly thermally conducting state refers to the dominant conduction by electrons (no magnetic field) and the 'off' low thermally conducting state refers to the dominant conduction by phonons (magnetic field is applied).

2.2 Performance

As part of the millikelvin cryocooler project, the MR heat switch has been further developed resulting in an improved performance compared to that of the tungsten samples tested and discussed in Bartlett et. al[11]. A sample, shown in Figure 6, has been cut from the tungsten rods that will be used to make the heat switches for the millikelvin cryocooler and has been thermally tested with very good results. Due to the very short path length (6 mm) of the sample it has been incredibly difficult to measure the Residual Resistivity Ratio (RRR) and the on (zero magnetic field) conductivity and so lower limits are given in this paper. Before being integrated into the cryocooler, one of the heat switches, which has a path length of 31 cm will be fully thermally characterized.

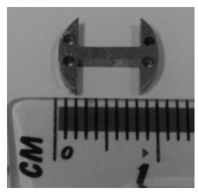

Figure 6: Single crystal tungsten sample.

The lower limit of the RRR of the tungsten sample has been ascertained by measuring the room temperature and 4.2 K electrical resistivity using an Agilent 34420A nanoVolt/microOhm meter which is capable of measuring to 0.1nV. The measurement of RRR is performed by passing a fixed current (0.5 A at room temperature and 20A at 4.2 K) and measuring the voltage drop along the sample, the electrical resistance is then calculated from Ohms law and subsequently the electrical resistivity. The room temperature electrical resistivity was measured to be 6.1 x 10^{-8} Ωm whilst the 4.2 K resistivity of 2.0 x 10^{-13} Ωm is within the voltage noise of 10 nV giving a lower limit of the RRR of 300,000. The lower limit for the on thermal conductivity has been measured to be 230 W/cm/K at 4 K. Figure 7 shows how the measured off thermal conductivity varies in the temperature range 0.3 K to 4 K. The 1.0 and 1.5 Tesla data have been measured and the 2.0 T has been calculated from the 1.5 T data by using the ratio of the square of the magnetic fields[12]. From these measurements, the MR heat switches used in the millikelvin cryocooler will have a minimum switching ratio of 1.2 x 10^4 at 4 K and an estimated switching ratio of 3.5x10^4 at 100 mK.

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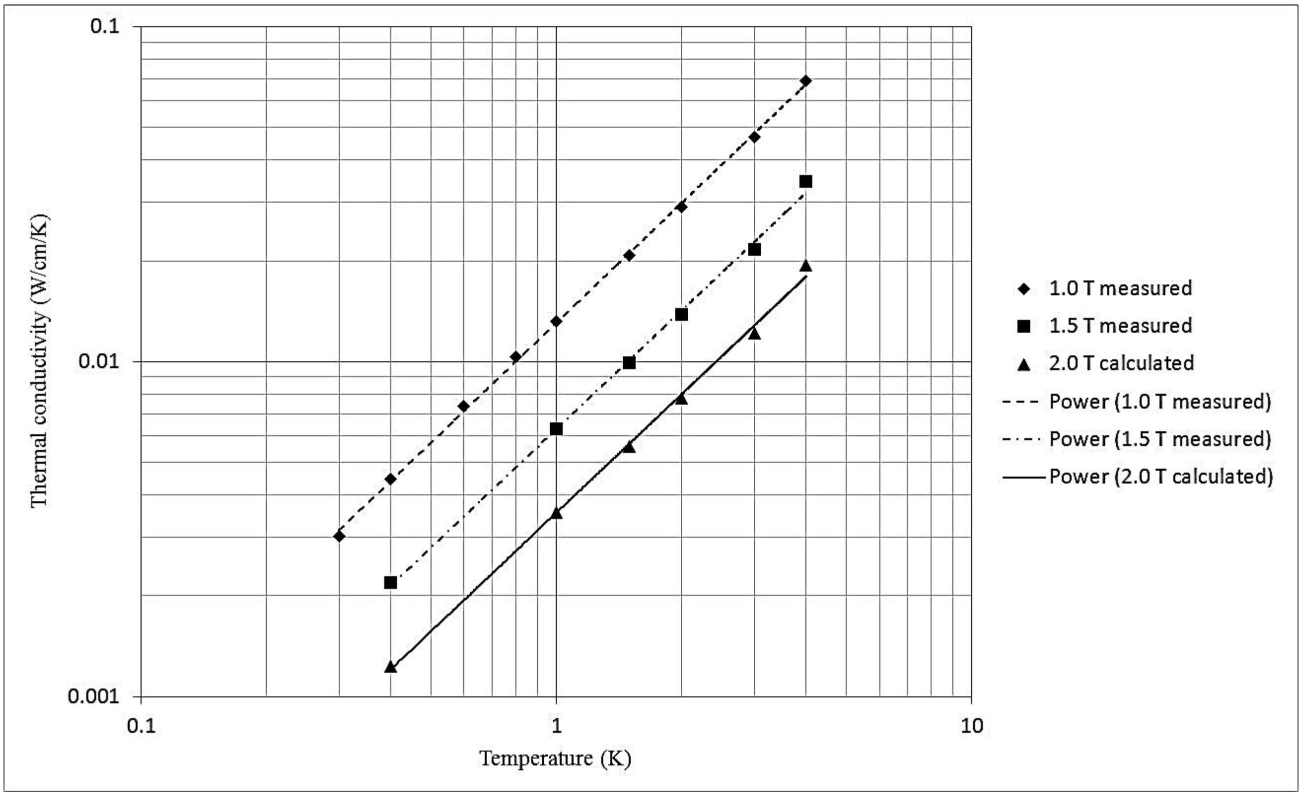

Figure 7: Measured off thermal conductivity of single crystal tungsten sample at 1.0 and 1.5 T and calculated off thermal conductivity at 2.0 T.

3. MILLIKELVIN CRYOCOOLER

The millikelvin cryocooler (mKCC) has been designed with ease of use in mind, to make cryogenics in the millikelvin range as simple for the user as operating a 4 K cryocooler. The mKCC is a single module which easily bolts onto a 4 K interface and provides an interface to the user which can range from <100 mK to 4 K. Although the configuration is two dADRs operating in tandem to cool the millikelvin stage, the user will not need to have prior knowledge about ADR operation as this will be fully automated system with the user only having to specify the operating temperature of the continuous stage. A 3D model of the mKCC is shown in Figure 8.

The mKCC will have a height of 355 mm (excluding the millikelvin shield) a width of 120 mm and a depth of 56 mm. The estimated total mass is 8.3 kg, of which 6.6 kg is due to the mass of the magnets and the magnet shields.

The design requirements of the mKCC were to operate from a 4 K bath provided by a PTR and to continuously provide 1 μW of cooling power at 100 mK. The magnets had the design requirements of a 2 T magnetic field with a ramp time of 20-30 seconds. This lead to a preliminary design of the magnets (provided by Scientific Magnetics) giving an inner bore diameter of 26 mm, an outer bore diameter of 43.6 mm and a height of 30 mm.

The nature of the CADR (whereby tandem dADRs are operated alternately), requires that the recycle time of each dADR is less than the hold time so that the millikelvin stage temperature can be maintained continuously. Based on a minimum magnet ramp time of 20 – 30 seconds, the target recycling time of each dADR was set to be 10 minutes and to give a margin for error, the target hold time of each dADR was set to be 60 minutes.

To design the mKCC, a full mathematical thermal model of the mKCC was generated based on that produced and validated on the ESA ADR. The model is a 0.1 second time step dynamic model and calculates all heat loads within the system, the temperatures of the paramagnetic materials within each dADR throughout its cycle, as well as the recycle and hold times. The design of the mKCC can be broken down into two sub-assemblies; the ADR insert assembly and the magnet assembly which are discussed below in sections 3.1 and 3.2 respectively. The predicted performance based on

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the model results is given in section 3.3 and this is backed up with the preliminary results of the prototype tests presented in section 3.4.

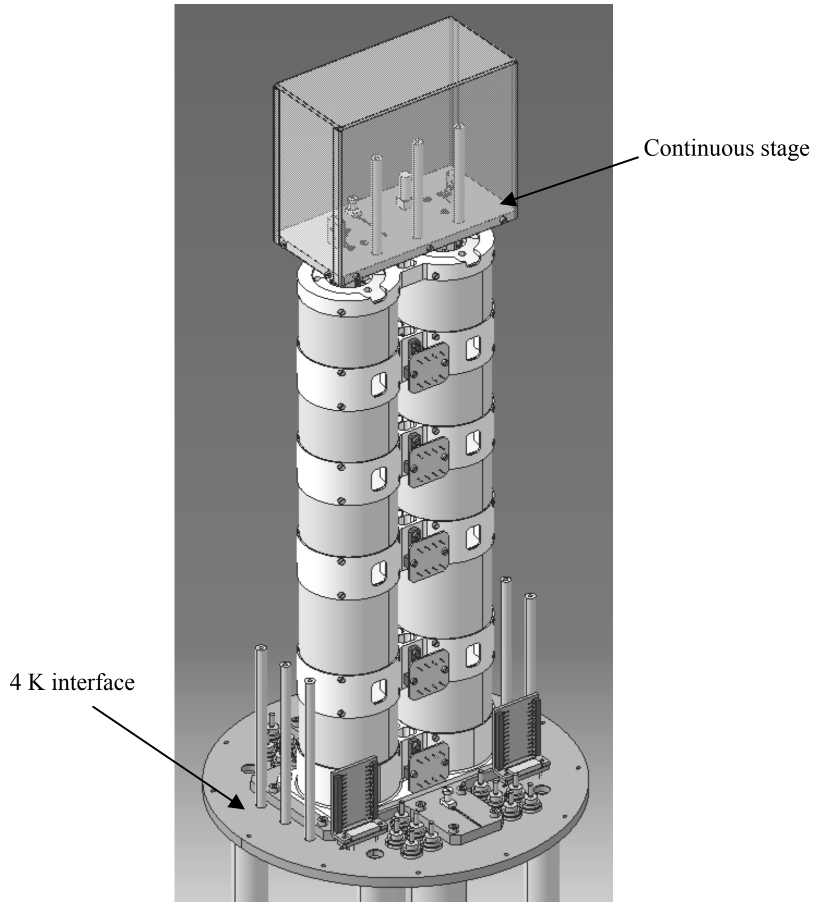

Figure 8: 3D model of the millikelvin cryocooler

3.1 ADR insert assembly

The ADR insert assembly is comprised of the paramagnetic materials, the heat switches and the suspension units and is shown in Figure 9.

The paramagnetic materials used in the mKCC are Gadolinium Gallium Garnet (GGG) as the high temperature stage and CPA as the low temperature stage. The GGG pill has a 24 mm diameter and is 45 mm in length and contains 132 mmol (~133 g) of GGG. It is a compressed powdered pill mixed together with a small amount of Apiezon-N grease to aid thermal transfer. The CPA pill also has a 24 mm diameter and is 30 mm in length. It contains 44 mmol (~22 g) of CPA and the CPA crystals are grown directly onto the thermal bus within the outer housing. Both pills have a similar construction in terms of G10 fibre glass outer housings, G10 sealing end caps and gold plated copper end plates onto which are brazed the thermal straps. The only difference is that the CPA pill also has 364 0.25 mm diameter gold plated copper wires within it acting as the thermal bus. These are brazed onto the end plates. Figure 10 shows as exploded view of the CPA pill.

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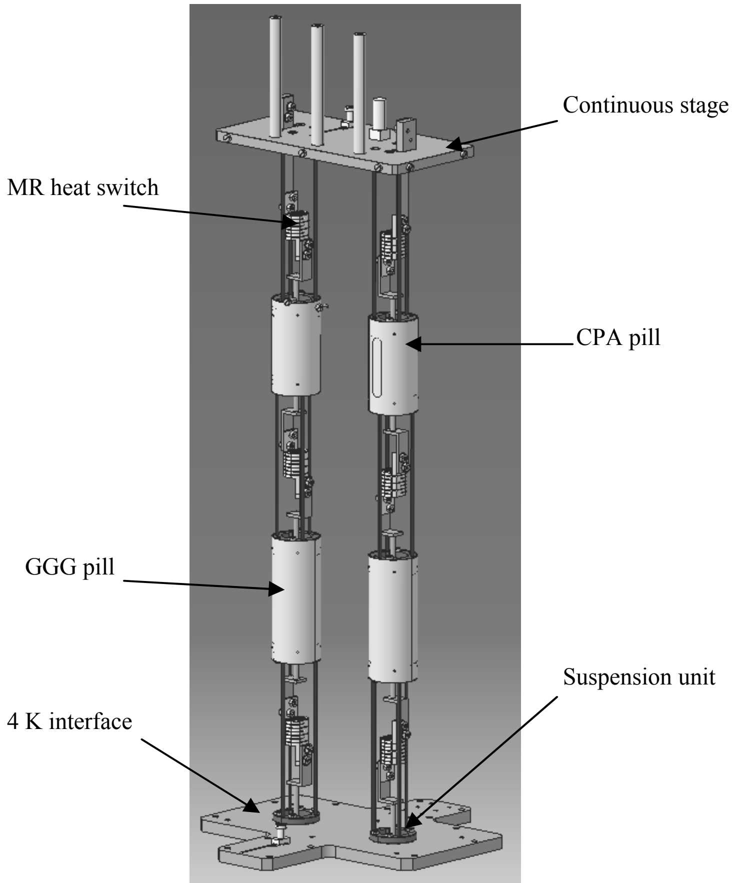

Figure 9: ADR insert assembly.

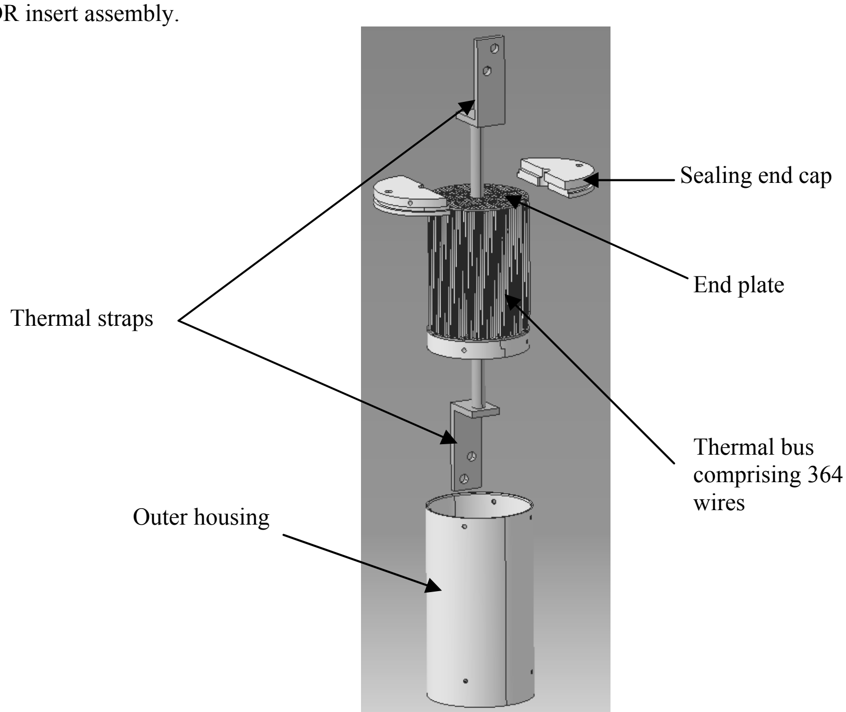

Figure 10: Exploded view of a CPA pill.

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All six heat switches used in the mKCC are single crystal tungsten magnetoresistive heat switches. Each has a free path length of 31 cm, an outer diameter of 12.5 mm and 7 layers (see Figure 11 left). The total height of each heat switch is 32.3 mm. This will be the first ADR to operate using only tungsten heat switches.

Traditionally Kevlar has been used to suspend the paramagnetic materials within the bore of their magnets but this uses up valuable space and makes assembly of the ADR more difficult. Instead of Kevlar, a suspension unit will be used which will significantly reduce the complexity of the ADR insert. There are six suspension units in total, each consisting of two G10 interface rings and three 2 mm diameter Vespel^{TM} SP1 rods (see Figure 11 right). These suspension units are simply screwed into place in between the different stages as shown in Figure 9.

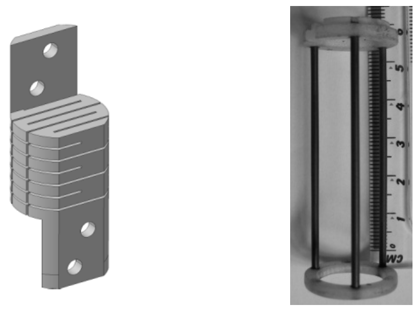

Figure 11: left: The MR heat switch for the mKCC; right: The suspension unit

3.2 Magnet sub-assembly

The magnet assembly consists of the magnets, magnetic shields and the spacer tubes which are used to space out the magnets in the stack and provide mechanical stability along the length of the stack. The mKCC operates using ten 2.5-3.0 Amp 2 T magnets which can ramp in 20 seconds. The outer diameter of each magnet is 43.6 mm, inner diameter is 26 mm for the heat switch magnets and 28 mm for the pill magnets, the CPA and heat switch magnets are 30 mm in length and the GGG magnets are 45 mm in length.

Figure 12 shows a preliminary assembly of the magnet sub-assembly with 9 of the magnets. Only 9 are shown as the other one is currently being used for testing.

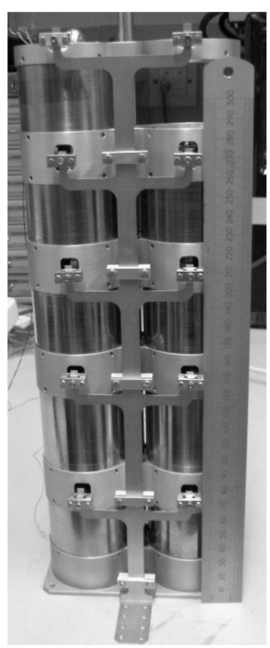

Figure 12: Magnet sub-assembly showing 9 magnets in position.

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Stray magnetic field is a concern for the majority of users who do not want interference with their sensitive instruments/detectors. The magnets used in the millikelvin cryocooler are each housed within their own magnetic shield. The stray magnetic field has been modelled around the entire magnet assembly at different intervals during the cryocooler operation to determine how the stray field varies as different magnets are switched on and off. Figure 13 shows the stray field surrounding the mKCC at a radial distance of 150 mm from the centre of the cooler. The dADR on the right in the figure is the cold dADR keeping the continuous stage at its operating temperature, the one on the left is the recycling dADR which is at the stage of recycling the CPA pill. In the cold dADR chain, there are 3 magnets at 2 T (from the top, the second, third and fifth magnet), in the recycling dADR there are 4 magnets at 2 T (from the top, the first, second, third and fifth magnet). The maximum stray field is 5.79 mT (57.9 gauss).

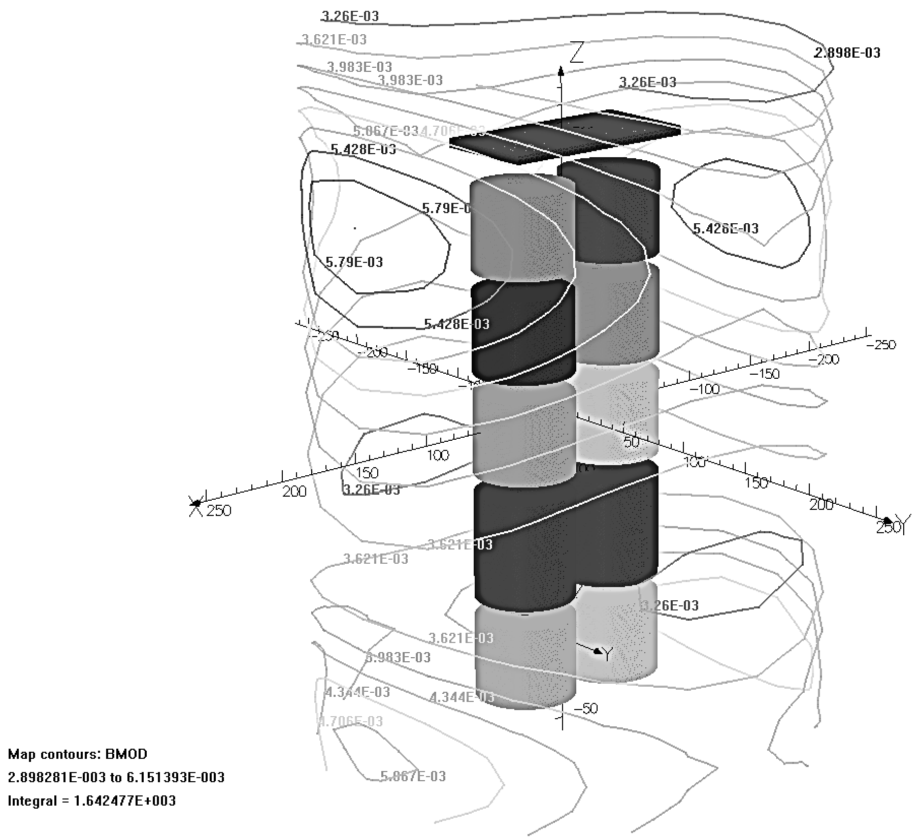

Figure 13: Stray field around mKCC at a distance of 150 mm from the centre of the cryocooler.

Figure 14 shows the stray magnetic field at the continuous stage with the recycling dADR now on the right of the figure and the cold dADR on the left. The maximum stray magnetic field at the surface of the continuous stage is 69.1 mT (691 gauss). Figure 15 shows how the stray magnetic field varies with height (up to 100 mm) above the continuous stage; within the first 10 mm the field has decreased from 69.1 mT (691 gauss) at the surface of the plate to ~45 mT, (450 gauss) after 20 mm this has decreased further to 30 mT (300 gauss) and after 50 mm the stray field is below 10 mT (100 gauss).

The magnetic shielding used in the mKCC has been designed to prevent stray field interference between the paramagnetic material and heat switch stages and not specifically designed for shielding the continuous stage. Further magnetic shielding can easily be introduced at the continuous stage (due to the low intrinsic field from the cooler) to meet user requirements.

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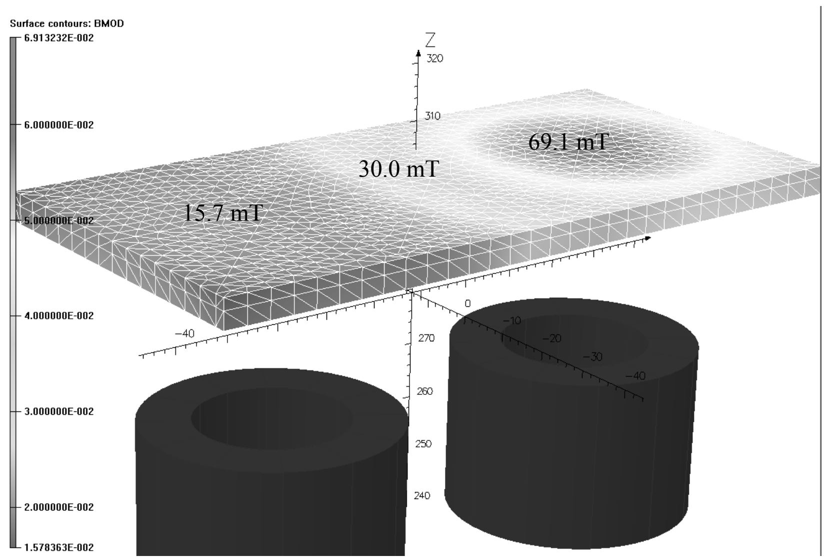

Figure 14: Stray magnetic field at the continuous stage.

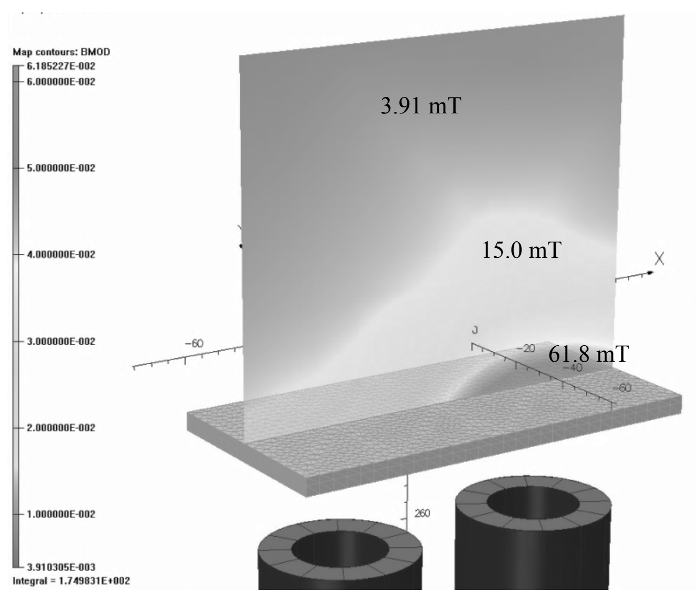

Figure 15: Stray magnetic field within the continuous stage sample space volume.

3.3 Predicted performance

Based on the mathematical thermal modelling, the estimated recycle time for each dADR is 6.9 minutes. The predicted temperatures of the GGG and CPA pills during recycling are shown in Figure 16 below. The maximum predicted temperatures are 4.83 K for the GGG and 1.74 K for the CPA with the CPA estimated to start demagnetization from 1.6 K. In this model magnetization of the paramagnetic materials will take 60 seconds with a 30 second switching time for the MR heat switches.

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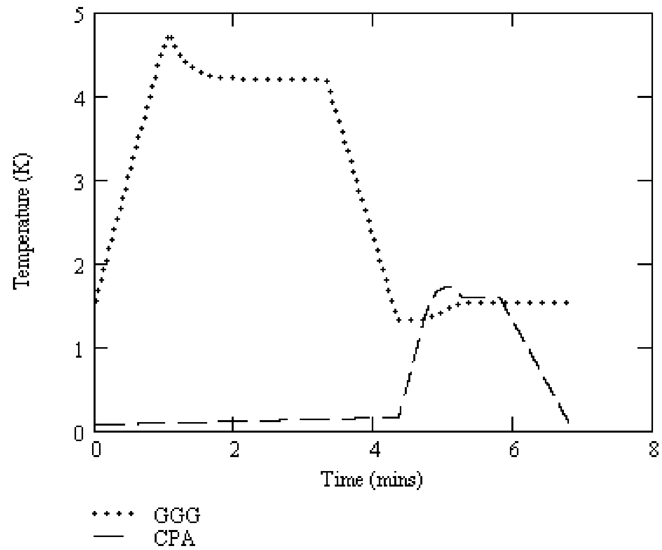

Figure 16: Predicted GGG and CPA temperatures during recycling.

The base operating temperature with a 1 μW applied heat load is predicted to be 80 mK. With an applied power to the continuous stage of 1 μW and an operating temperature of 100 mK the estimated hold time for each dADR is 60.5 minutes. During this hold time the typical total heat load to the cold CPA pill is 4.5 μW (including applied power) with a peak heat load of 8.4 μW occurring during the magnetization phase of the CPA pill in the recycling dADR.

For the cryocooler to work, theoretically the hold time needs to just exceed or equal the recycle time. However a large margin has been added into the design to accommodate for any time constants that may be associated with extracting heat from the pills and to allow for a smooth switch over of control of the continuous stage from one dADR to the other. This margin, if unnecessary in practice, would mean that the cryocooler could, based on modelling have a higher cooling power at 100 mK of up to 7 microwatts; an applied heat load of 7 microwatts produces an estimated hold time of 16.5 minutes

Operation of the millikelvin cryocooler will be fully automated using an electronic control program which will control all magnet power supplies, run a servo temperature control of the millikelvin stage and log all temperature sensor readings. It will have a simple user interface allowing the user to specify the operating temperature and will display logged data and information on the operation of the cryocooler. The predicted thermal stability is ≤ 1 μK even during the switch over from one dADR to the other; because the thermal conductivity of the MR heat switch is proportional to the applied magnetic field, it is anticipated that the switch over can be carefully controlled by manipulating the magnetic field thereby avoiding any thermal spikes on the millikelvin stage.

It should be noted that whilst the mKCC has been designed for ground operation, adaptation for space will only require modest changes due to the utilization of similar components to the ESA ADR.

3.4 Prototype CPA pill testing

A prototype CPA pill has been tested from a 4 K bath using one of the 2 T magnets designed and built for the mKCC. The aim of the prototype was to validate the CPA pill design and growth method by analyzing the response of the pill to a rapidly changing magnetic field. With the exception of the thermal straps which have been modified to aid testing, the CPA pill has been made to the specification of the CPA pills that will be used in the mKCC. Figure 17 shows the experimental set-up; the CPA pill is isolated from the 4 K base plate by a Vespel SP1/G10 suspension unit and is connected to the 4 K base plate via a mechanical heat switch. The magnet is connected to the 4 K baseplate via a gold plated copper support tube.

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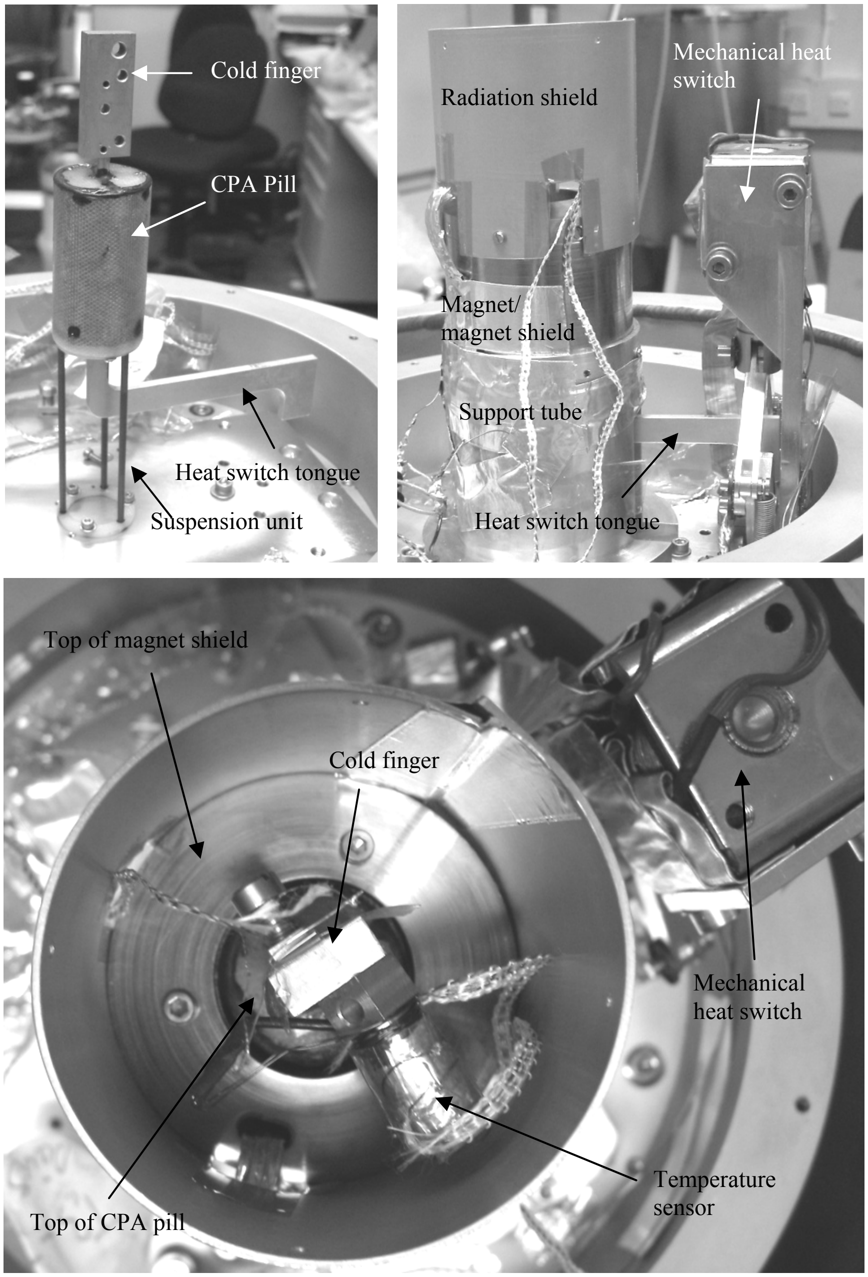

Figure 17: Experimental set up for testing the prototype CPA pill: top left: CPA pill on its suspension unit; top right: Magnet, magnet shield and radiation shield are added over the CPA pill; bottom: looking down onto the CPA and magnet assembly.

The preliminary tests have been extremely encouraging with a full cycle of the CPA pill from 4 K to 173 mK (magnetization, cooling to the bath and demagnetization) demonstrated in under 2.5 minutes. This validates the fast recycling times predicted by the thermal model and from the graph shown in Figure 18 it can be seen that there is an excellent thermal link between the CPA crystals and the thermal bus; the pill responds immediately to the application and the removal of the magnetic field with minimal thermal lag and the need for only 90 seconds of cooling time after magnetization is complete. This gives us good confidence in our full cryocooler model. It should be noted that the noise shown in Figure 18 at the higher temperatures is due to the insensitivity at this temperature of the Ruthenium Oxide temperature sensor which typically is only used in the millikelvin region.

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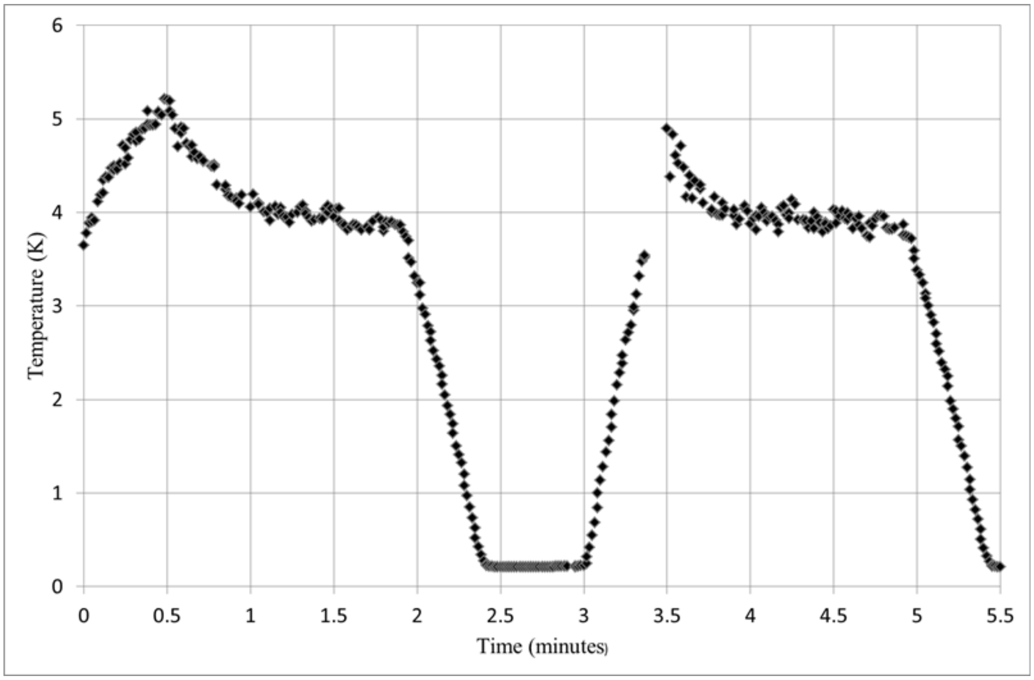

Figure 18: Temperature of the prototype CPA pill during two magnetization and demagnetization cycles

4. CONCLUSIONS

A fully automated millikelvin cryocooler (mKCC) has been designed which will provide continuous cooling from < 100 mK to 4 K with a predicted maximum cooling power at 100 mK of 7μW The design for this cooler has evolved from the heritage of the ESA ADR and the continued development of the tungsten magnetoresistive heat switch. There is good confidence in the design based on the results from testing the prototype CPA pill which proved that the CPA pill will respond immediately to the application and removal of a 2 T magnetic field in a 30 second time frame. The mKCC has been designed to be user friendly and would be highly beneficial to any user requiring a continuous operating temperature from sub 100 mK to 4 K. The system is currently in the assembly phase with full system testing due to start in August 2012.

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REFERENCES

[1] Debye P., Annals of Physics, Series 4, Volume 81, 1154-1160 (1926)
[2] Giauque W. F., "A thermodynamic treatment of certain magnetic effects. A proposed method of producing temperatures considerably below 1 degree absolute", Journal of the American Chemistry Society, 49, 1864 (1927).
[3] De Haas W. J., Wiersma E. C., Kramers H. A., "Experiments on adiabatic cooling of paramagnetic salts in magnetic fields", Physica 1, 1-13 (1933).
[4] Giauque W. F., MacDougall D. P., "Attainment of temperatures below 1º absolute by demagnetization of Gd2(SO4)2 • 8H2O", Physical Review, 43, 768 (1933).

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[5] Kurti N., Simon F. E., “Production of very low temperatures by the magnetic method: supraconductivity of cadmium”, Nature (London), 133, 907-908 (1934).
[6] Hepburn I. D., Davenport I., Smith A., “Adiabatic Demagnetization Refrigerators for future sub-millimetre space missions” Space Science Reviews 74, 215-223 (1995).
[7] Bartlett J., Hardy G., Hepburn I. D., Brockley-Blatt C., Coker P., Crofts E., Winter B., Milward S., Stafford-Allen R., Brownhill M., Reed J., Linder M., Rando N., “Improved performance of an engineering model cryogen free double adiabatic demagnetization refrigerator”, Cryogenics 50 (9), 582-590 (2010).
[8] Bradshaw T., “Technology developments on the 4K cooling system for Planck and FIRST”, Sixth European Symposium on Space Environmental Control Systems, 465 –470, (1997).
[9] Gas-gap heat switch supplied by L. Duband of CEA SBT, Grenoble.
[10] Batdalov A. B., Red’ko N. A., “Lattice and electronic thermal conductivities of pure tungsten at low temperatures”, Soviet Physics Solid State 22(4), April, 664 – 666 (1980)
[11] Bartlett J., Hardy G., Hepburn I. D., Ray R., Weatherstone S., “Thermal characterization of a tungsten magnetoresistive heat switch”, Cryogenics 50 (9), 647–652 (2010).
[12] Wagner D. K., “Lattice Thermal Conductivity and High-Field Electrical and Thermal Magnetoconductivities of Tungsten”, Physical Review B, 5(2), 336 – 347 (1972).

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