A Miniature Continuous Adiabatic Demagnetization Refrigerator with compact shielded superconducting magnets.

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ABSTRACT

Cryogenic detectors for astrophysics depend on cryocoolers capable of achieving temperatures below ≈ 100 mK. In order to provide continuous cooling at 50 mK for space or laboratory applications, we are designing a miniature adiabatic demagnetization refrigerator (MADR) anchored at a reservoir at 5 K. Continuous cooling is obtained by the use of several paramagnetic pills placed in series with heat switches. All operations are fully electronic and this technology can be adapted fairly easily for a wide range of temperatures and cooling powers. We are focusing on reducing the size and mass of the cooler. For that purpose we have developed and tested magnetoresistive heat switches based on single crystals of tungsten. Several superconducting magnets are required for this cooler and we have designed and manufactured compact magnets. A special focus has been put on the reduction of parasitic magnetic fields in the cold stage, while minimizing the mass of the shields. A prototype continuous MADR, using magnetoresistive heat switches, small paramagnetic pills and compact magnets has been tested. A design of MADR that will provide $\approx 5\ \mu$W of continuous cooling down to 50 mK is described.

Keywords: Cryogenics, ADR, Heat switches, Magnetic Shielding

1. INTRODUCTION

Cryogenics detectors are required for many measurements in astronomy and astrophysics. The sensitivity of bolometers and microcalorimeters is greatly enhanced by lowering their temperature, down to 50 to 100 mK. Cryogenic coolers exists for this range of temperature but improving their reliability and easing their integration for space observation is desirable. To achieve temperatures under 200 mK, adiabatic demagnetization refrigerator (ADR) and dilution refrigerators seem the most promising technologies.

Dilution refrigerators have the disadvantage of requiring plumbing that may be subject to plugging. Despite this disadvantage, a dilution fridge will be used for the Planck mission. An open cycle of helium is used, meaning that helium is evacuated to the outer space. In our opinion, the main drawback for future applications is that the quantity of helium embarked is expected to be the limit for the mission life.

ADRs can be cycled indefinitely and, with appropriate design can even provide continuous cooling. The disadvantage in that case is the need for several heat switches and of magnetic field. Magnetic fields have to be shielded, at the cost of a significant increase in mass and size. Our goal is to design and test a concept for a miniature ADR (MADR), with light shielding, reliable heat switches and the capacity to provide more than 5 μW at 100 mK.

2. OVERVIEW

2.1. Conventional ADR

Conventional ADRs[1] are composed of three main components : a paramagnetic salt, a magnet and a heat switch. The salt is usually in the form of a pill. The magnetic field of the magnet, superconducting, ramps up and down at each cycle. The heat switch has to be turned on during the isothermal magnetization process and off for the adiabatic demagnetization, when the ADR has to be thermally insulated from the bath.

The refrigeration cycle exploits the interaction between the atomic magnetic moments in a paramagnetic material (often a salt) and an externally applied magnetic field. When a magnetic field is applied to a paramagnetic refrigerant, its magnetic spins are aligned and ordered. In the first phase of the cycle, this process is done at constant temperature leading to an decrease of the entropy of the salt. The next step is an adiabatic demagnetization of the salt leading to the decrease of temperature of the salt and of the cold stage. Cooling cycle

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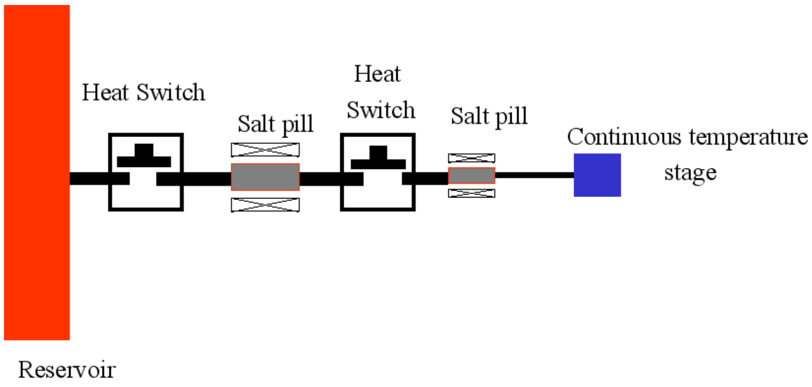

Figure 1. Schematic of a 2-stage continuous ADR including a succession of 2 heat switches and 2 paramagnetic pills and their associated magnets.

of conventional ADRs require a recycling phase during which the temperature of the salt and of the detectors are brought to the bath temperature.

Usually, ADRs are used for providing cooling in the range of 20 mK up to 20 K or more. It is particulary efficient at low temperatures, when the heat capacity of the salt itself is very low compared to its magnetic entropy. ADR are used widely for laboratory experiment. It has also been successfully used in a short rocket flight[2] and balloon born experiment.[3] To our knowledge it has never been used in space experiments, partly because of the disadvantage of its mass and size and of the difficulty of developing reliable and efficient heat switches.

2.2. Continuous ADR

Our goal is to scale down the size of the pills and of the magnet used for the magnetization. A way to limit these sizes is to implement a continuous ADR that open the possibility of multiple recycling of the pills. This process has been described by Shirron et al[4] and is represented for 2 stages in figure 1. Any number of stages -including a heat switch and a salt pill with its magnet - can be added in series to this scheme. The temperature of the last pill (starting from the reservoir) is kept at a constant temperature all the time. During its magnetization it is in thermal contact with the previous pill whose temperature is maintained below the nominal temperature of the cooler. During the demagnetization, the thermal contact between the two pills is cut and the demagnetization rate is adjusted to compensate exactly for the thermal losses to the cold stage. Simplified variation of temperature and magnetic field are presented in figure 2.

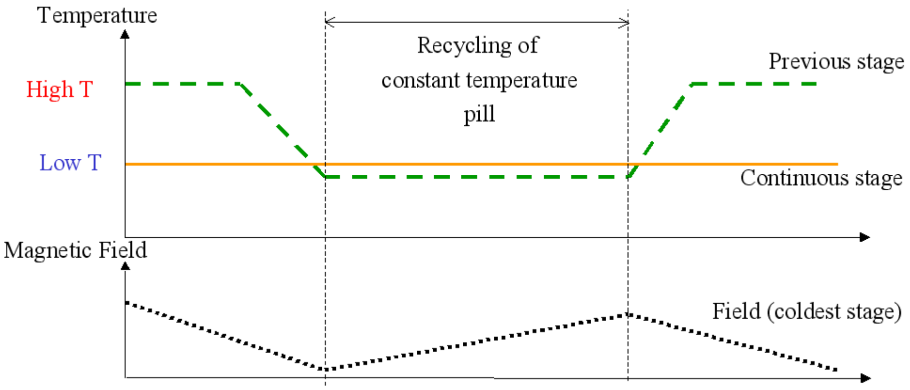

Figure 2. Schematic variations of temperature and magnetic field as a function of time in a continuous ADR.

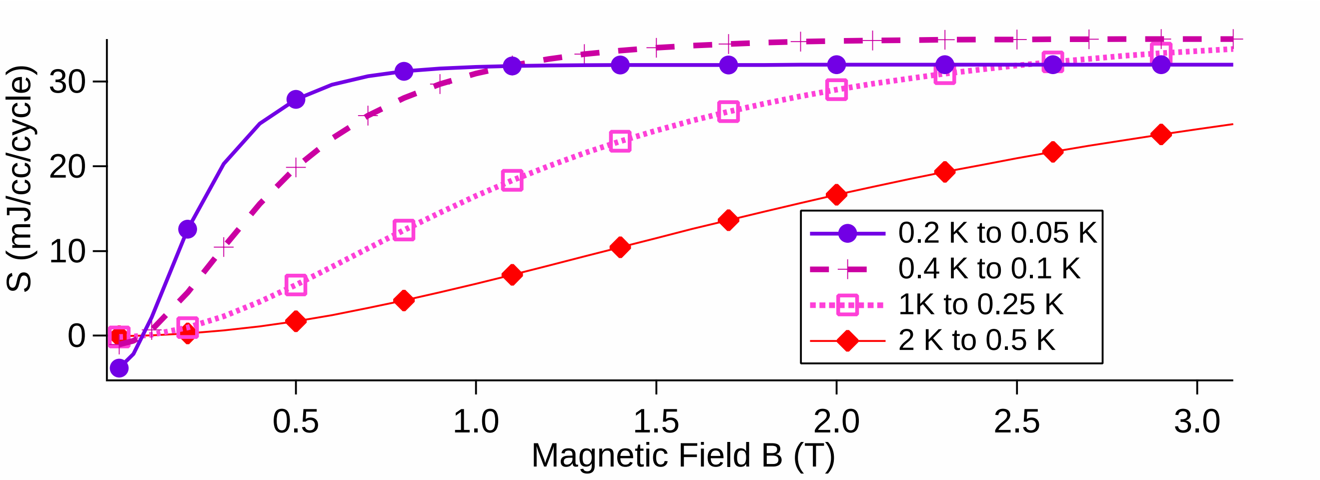

Figure 3. Theoretical value of the entropy that can be extracted per pill of CPA at low temperatures as a function of maximum magnetic field. Plots are presented for different maximum and minimum temperatures in a ratio of 4 to 1. Entropy has been calculated using the model of free ion approximation.

For a conventional ADR, the cooling of the cold plate and detectors reduces the available entropy of the pills once a cold temperature is achieved. Moreover, the size of the pill has to be designed to provide a sufficiently long hold time. For a continuous ADR, theoretically, the pills can be cycled as often as possible, thus only a small amount of heat has to be extracted at each cycle. It opens the possibility for using small pills and small magnetic fields.

2.3. Characteristics of MADR

The magnetic field and the size of the pills used are directly dependent on the heat that has to be extracted per cycle. For a given number of stages, the shorter the cycle is, the less heat has to be extracted per cycle. Therefore, by increasing the speed of cycling, it is possible to reduce the size of the pills and the corresponding magnets.

The maximum cycling frequency depends both on the minimum switching time of the heat switches and on the eddy current heating in the magnet for the pills. For the magnetoresistive heat switches on which we are working, the switching time is also mainly dependant on the eddy current, both in the copper bus to the tungsten crystal and in the magnetic shield. The latter can cause the quench of the magnet during the ramp. We demonstrated, with the magnetoresistive switches described in this paper that a switching time of 20 to 25 s can be achieved without prohibitive eddy current heating. The time of switching has to be kept to a small part of the overall time of the cycle, since it could be considered dead time in the optimization of the heat transfers. An overall cycle time of 500 s is achievable.

2.4. Temperature range

Thanks to the design in series, any range of temperature can be achieved depending on the number of stages. The type of salt and the magnetic field have to be adapted to the desired temperature.

At different temperature ranges, we could imagine using continuous cooling using ^{3}He or ^{4}He refrigerator together with a series of 2 or 3 ADR. It would allow it to start at low temperatures and reduce the maximum temperature and magnetic field necessary. Also a longer series of pills could be used for wider temperature span. We imagined and described[5] a design that could be used to realize cooling from a reservoir at 5 K to 50 mK. It is described in the last part of this paper.

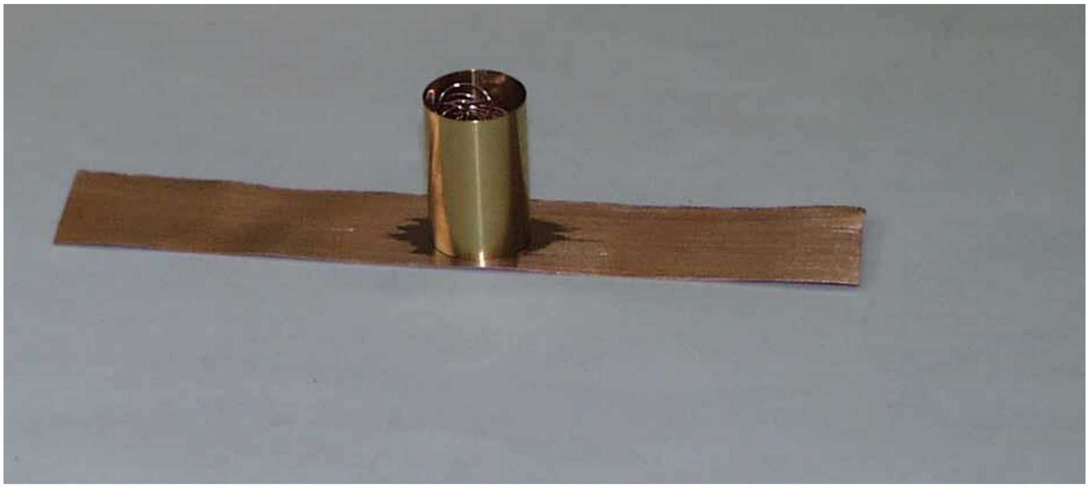

Figure 4. Salt pill housing including copper wires brazed to the copper bus and a brass cylinder soldered to the bus.

3. SALT PILLS

Depending on the range of temperature several paramagnetic salts can be used. Traditionally, ferric ammonium alum (FAA) has been used in laboratory. It has the advantage of high solubility in water and hence crystals are easy to grow. Its main disadvantage is that it decomposes at about 39 °Cwhich makes it a bad candidate for space based applications. Also, for low temperatures, salts like chromic potassium alum (CPA) have a higher cooling power per volume. CPA has been chosen. Its decomposition temperature is 89 °Cand therefore can sustain a temperature of 50 °Cwithout any damage.

The salt is grown in a brass can containing copper wires (figure 4) brazed to a thermal bus. Sealing is necessary to prevent the dehydration of the salt. It is achieved by sealing with Stycast 2850 a brass lid on the can after the salt is grown.[5]

For temperature higher than 2 Kelvin, CPA does not provides good cooling capacity per unit of volume (figure 3). For the highest-temperature cold stage we will use gadolinium gallium garnet (GGG) as the paramagnetic material. We have used GGG in the past to cool from a starting temperature of 4.2 K to a temperatures of ≈ 1 K[6]; it is suitable for even higher starting temperatures as well. GGG pills are available commercially and have superior materials properties to both CPA and FAA. Since GGG is not a salt, it does not need to be sealed or grown in place. Its thermal conductivity is large enough that we will make thermal contact to it by clamping it to the copper cold stage. There is a wide range of other possible paramagnetic refrigerants that could be used for even higher-temperature stages.[7]

4. HEAT SWITCHES

4.1. Kind of heat switches

Heat switches for cryogenics falls in four main categories : mechanical, gas-gap, superconducting and magnetoresistive. To fit with our requirements of quick switching time and reliability, magnetoresistive, superconducting and passive gas-gap are possible. We worked extensively on the design of magnetoresistive heat switches based on tungsten crystal. Switching time depends only on the ramping of the magnet, and the on/off ratio of the conductivity is similar over a wide range of temperature (measured from 150 mK to 10 K). This made it a good candidate for this application. If results are well reproducible for high magnetic field, the maximum conductivity depends mainly on the purity and size of the crystal. All the crystal we could obtain exhibited residual resistivity ratio (RRR) of around 200 or less. (The advertised purity is from 99.6 to 99.9%). In order to improve the efficiency of the cooler, it is desirable to find crystal of RRR > 500.

4.2. Other heat switches

Another solution for heat switches for this design are passive gas-gap heat switches which have been used by Shirron et al.[8] They offer good switching ratio and a quick switching time. On one hand, being passive is an advantage in the way it does not require any control and limits the complexity of the control. On the other hand, it means that each switch has to be optimized for a definite set of temperatures and limits the adaptability of the cooler. Nevertheless, they are promising for this design. Mechanical heat switches have been rejected because of their size and comparatively low reliability. Active gas-gap heat switches usually have long switching time (over a minute) or low efficiency and are therefore not suitable for our fast cycling goal. Superconducting heat switches have been extensively used. They are really efficient for temperature under 1 K and could be used in the coldest parts of our design.

4.3. Conclusion heat switches

We measured thermal conductivities of tungsten crystal as a function of temperature and magnetic field. We proposed a design for magnetoresistive heat switches based on these crystals. We showed that such switches can be used for MADR. Finding crystal with higher electronic conduction - or purity- would allow an increase in the efficiency of these switches and reduce the lowest temperature reachable by the cooler. It seems feasible to find better crystals according to several published measurements. Other kinds of heat switches, including superconducting switches and gas-gap heat switches may be used for MADR depending on the temperature of the stage.

5. MAGNET AND PARASITIC MAGNETIC FIELD

5.1. Winding

The design of the magnets needs to takes into account several constraints. First, the magnet and especially their shielding are largely responsible for most of the mass and volume of the ADR. Also, the current used in the magnet will be a constraint in the design of the warm electronic and currents leads and it should be minimized. Finally, stray magnetic fields in the place of the detectors would have a negative impact on their sensitivity and reliability.

For a given central magnetic field, the mass of the shield is driven by the overall size of the magnet. Therefore, in order to reduce the mass of the shield itself, special care has to be taken to reduce the size of the coil of the magnet. Reducing the size of the coil for a constant magnetic field means increasing the current density in the wire. Commercial wires of NbTi exhibit maximum current density of around 50,000 to 60,000 A/m^2. Unless using the inconvenient and expensive wires of Nb $_3$Sn, it seems unlikely to achieve higher current density in the near future. For this current density, the size of the wires has to be chosen as small as possible to reduce the current in the wires. Commercial wires of 0.1 mm diameters are available.[9] A current of only 5 Amps would be enough to have the current density described earlier. It is in our objective to use such wires. Nevertheless, we choose to use wire of diameter 0.2 mm, which can be used with a current of 16 Amps for our first test. These choices kept the development cost lower and eased the winding of the coil.

5.2. Shield

The shield has to be carefully designed to achieve high efficiency with minimum mass. Magnetoresistive heat switches require the largest field and we focused our work on them. Smaller and thinner shields are required for the salt pills magnet but most of the work made for the heat switches is applicable to the pills. Numerical simulation for these calculations are of great help for this task and several codes are freely available.[10, 11]

We made our most efficient shield with Vanadium Permendur. Use of the more common silicon iron have been done at the expense of a slightly lower saturation field. To reduce the total mass and volume of the shield, we envisioned the possibility of using a layer of Vanadium Permendur followed by a layer of Cryoperm in order to take advantage of the higher saturation at lower field of the later (see figure 5). Numerical simulations showed that for the size and magnetic field of the magnets used for the heat switches, a single layer of Vanadium permendur was more efficient. For the pills, shield with a single layer of Cryoperm could be used and would

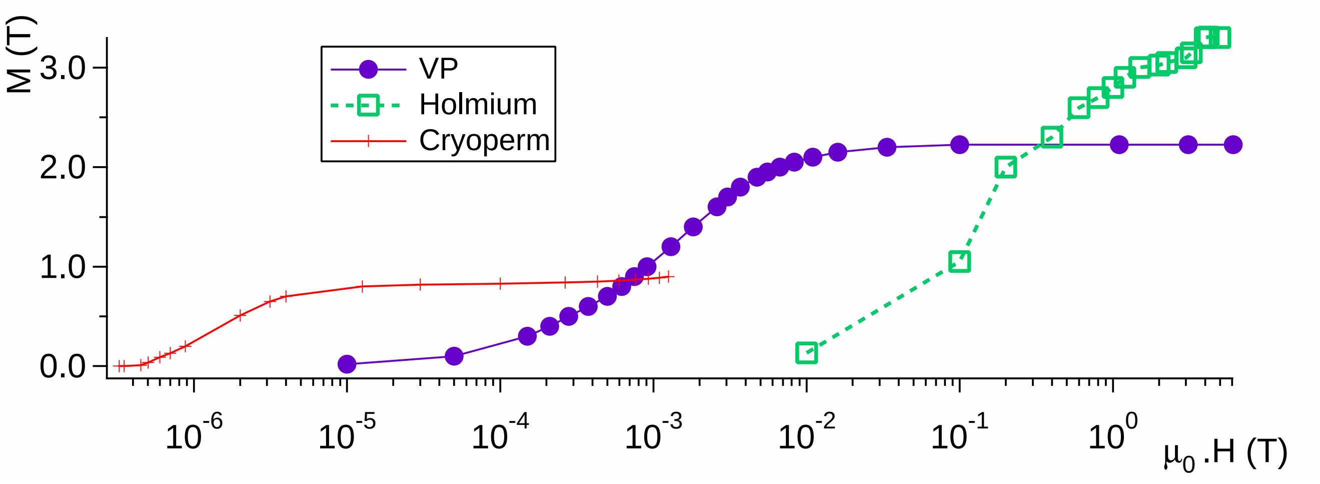

Figure 5. Magnetic properties of different material as function of magnetic field as has been used in our simulation. Data is from literature and our own experiments[13–15]

be smaller than vanadium permendur ones. In both case, having two layers of ferromagnetic material would increase the complexity for negligible improvements.

However, we also considered using a layer of superconducting material on the outside of the shield. The superconductor acts as a perfect diamagnetic material and reduces drastically the field outside. A preliminary experiment have been done with lead tape[12] and confirmed the feasibility and efficiency of such a setup. The limitation of that technique is the saturation field of the superconductors. Numerical simulations showed that Niobium can be used as the second layer and will provide additional attenuation of stray field of a factor of more than 100.

With proper shielding, the magnetic field at the position of the detectors can therefore be limited to less than 1 mT, or lower depending on the requirements. It should not limit the use of ADR for integration in low temperature experiments.

6. TWO STAGE PROTOTYPE AND TEST

A prototype of MADR with 2 stages and 2 magnetoresistive heat switches has been assembled and tested. It provided a continuous temperature of 450 mK with a reservoir temperature of 1.6K. This experiment shows the possibility of using miniature pills and magnets with fast cycling time. We are now working on the implementation of a third stage in order to reach a lower continuous temperature.

6.1. Experiment

For the prototype we built, the control of temperature and of the different phases of the cycle were fully automated using a computer controlled PID loop.[16] The temperature variations are shown in figure 7 and are discussed below. The continuous temperature achieved in this example is 450 mK, with a bath temperature of 1.6 K. This temperature is not a limit of the temperature ratio of an ADR. It depends on the size of the pills and of the efficiency of the switches.

6.2. Temperature stability

Each phase of the cycle is determined by measurements of temperature or of voltage (equivalent to field) of magnets, providing a fully self-controlled setup. Temperature is measured using ruthenium oxyde thermometers with a commercial ac-bridge.[17] Temperatures are acquired using GPIB connectors and a Labview data acquisition and control system. The temperature is controlled directly by modifying the current through the magnet of each pills. The power supply used for that experiment[18] allowed current variation of 100 mA.

On this example, the fluctuations of temperature was on the order of 1 mK, but we should emphasize that this is far from being the limit of stability. In fact, we believe that control of temperature, as well as temperature stability is a great advantage of ADR over other types of refrigerators. Indeed, the temperature is directly controlled by the magnetic field of the pills therefore, there is no need of heating and loss of efficiency.

Stability will be improved, in future experiments, by optimizing the PID parameters, using a more accurate power supply and increasing the frequency of temperature acquisition. The temperature acquisition and control of temperature was limited for practical purpose not linked to the ADR itself. The sampling rate and power supply sensitivity can therefore easily be increased.

Also, on this example, the mass of the cold plate during this experiment was of only a few grams of copper, with very low heat capacity. This choice was made in order to ease the repetition of several experiments. For an actual prototype, the thermal capacity of the cold stage can be increased without loss in efficiency since the last part is continuously cold and except at the very beginning of the experiment doesn't need additional cooling. Increasing the cold heat capacity will limit the temperature variations by the same order.

7. MADR 5K 50 MK

We designed a MADR able to reach the temperature of 50 mK starting at a bath temperature of 5K. We made the assumption that we were able to find tungsten crystal of purity at least 500. Also, this prototype could be realized using other types of heat switches, such as passive gas-gap, and achieve the same performance for even a lower mass.

If magnetoresistive heat switches have to be used, one can take advantage of the fact that they can be grouped in pairs in order to reduce the number of magnets (figure 8). The estimated size and magnetic field needed are summarized in table 1.

8. DISCUSSION AND CONCLUSION

We showed a design of MADR with the possibility of cooling from 5 K to 50 mK. Our design aimed at limiting the total mass of the prototype and a mass of around 4 kg would be enough to achieve such a large temperature ratio. We emphasized our work on the stray field at the position of the detectors and showed that a careful design of the shield would allow the use of ADR without perturbation on the detectors. The efficiency of the cooler would depend greatly on the characteristic of the heat switches. We suggested several type of heat switches with their limitation and advantages.

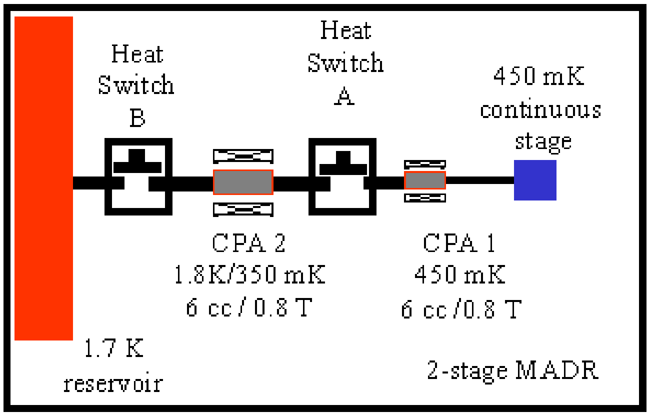

Figure 6. Experiment with two pills for a continuous temperature of 450 mK. The magnet and size for CPA1 (0.8 T/6 cc is oversized for this experiment allowing more freedom to tune the parameters

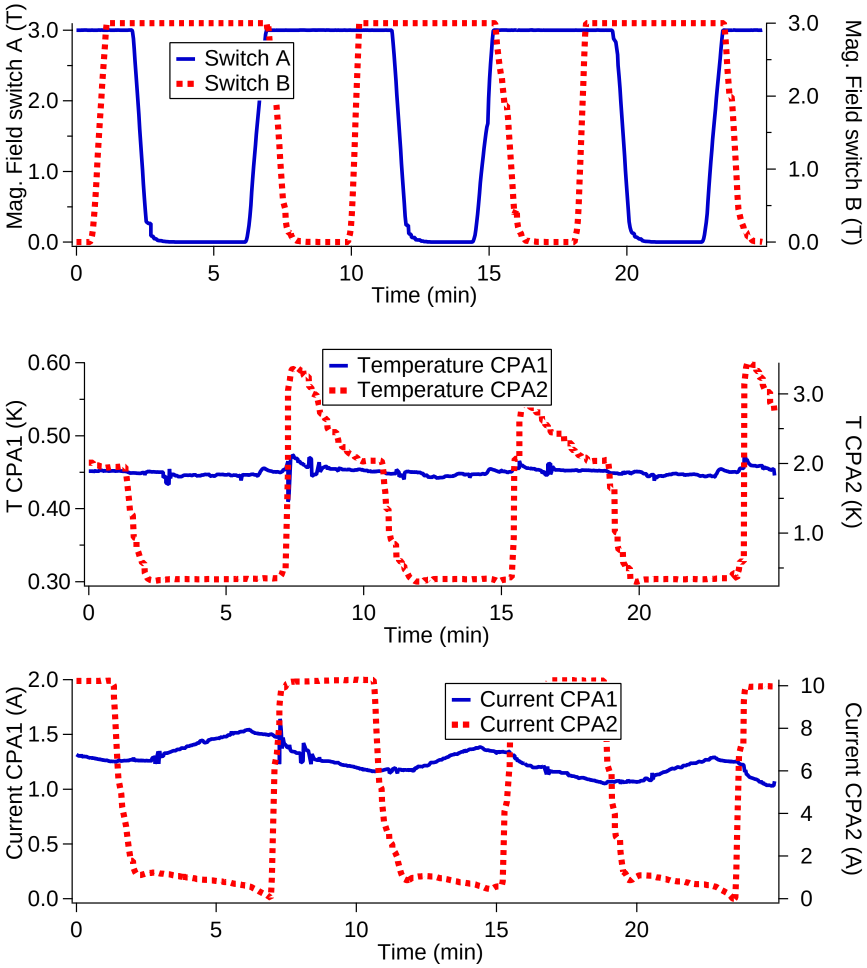

Figure 7. Validation of the principle by the test of a two-stage ADR. Top panel : magnetic field at center of heat switches vs time. Middle panel : Temperature of continuous stage (CPA1) and second stage (CPA2). Bottom panel : Current in the magnet for both stages. Values of the magnetic field are proportional to the values of the current with a ratio of around 15 A/T.

ACKNOWLEDGMENTS

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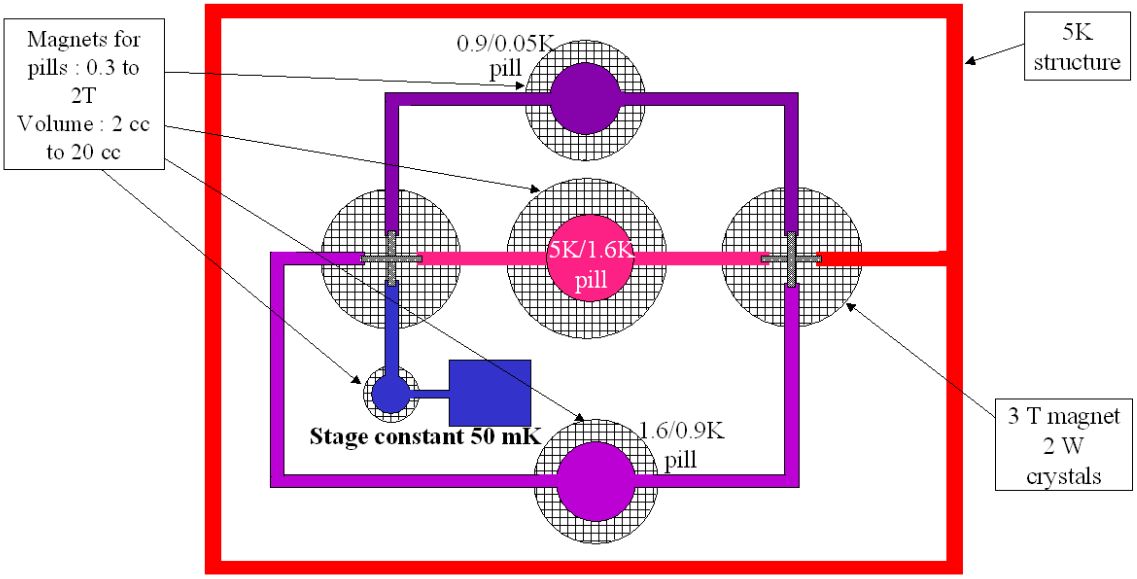

Figure 8. Schematic of a four-stage MADR. Structure is not fully represented. In order to reduce the size and mass of the prototype, a single magnet is used for two crystals. By placing them at slightly different high, thermal contact between them are avoided.

Table 1. Parameters for a four-stage MADR. Power is the heat load through the heat switches connecting the next stages. Q is heat extracted per cycle. size is size of paramagnetic pills and field, the magnetic field of the corresponding magnet. Tmin and Tmax are maximum and minimum temperature of the pill during a full cycle.

Pills	Tmax (K)	Tmin (K)	Power (uW)	Q (mJ)	size (cm^3)	Field (T)
CPA1	0.050	0.050	15.8	4	3	0.15
CPA2	0.8	0.047	35	8.6	10	1.2
CPA3	1.5	0.78	1100	250	15	1.5
GGG	5	1.46	2200	550	15	2.0

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