DESIGN OF A MINIATURE ADIABATIC DEMAGNETIZATION REFRIGERATOR

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ABSTRACT

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. We aim at a fast cycling process ($\approx$ 500 s) in order to reduce the size of the pills. For that purpose, we developed and tested magnetoresistive heat switches based on single crystals of tungsten. They provide good thermal performance for a very short switching time, depending only on the ramping speed of the magnet used. Magnets for cycling the pills and the heat switches are made from high current density NbTi wires. High permeability materials are used to shield these magnets, which is crucial to minimize stray magnetic fields. The field in the heat switch magnets is maximized using a holmium core. The magnets have been modelled using a numerical simulation. Small magnets($\approx$ 100 cm^3) with an operating field of 3 T have been designed and tested with a ramping time of less than 30 s. We have tested a single-stage MADR with a small pill, magnetoresistive heat switch and fast cycling time. These tests confirmed the feasibility of our design.

INTRODUCTION

The number of applications that require cooling of detectors to sub-Kelvin temperatures is rapidly increasing[1]. Bolometers and microcalorimeters cooled below 200 mK have important applications in observational astronomy. The utilization of these devices depends on the development of cryogenics under 200 mK. Current technologies for cooling detectors from an intermediate stage at 4 K to below 200 mK are two-fold: dilution refrigerators (DRs) and adiabatic demagnetization refrigerators (ADRs). Dilution refrigerators are fairly complex and require considerable plumbing. Typical ADRs allow cooling to temperatures under 50 mK but they are usually heavy (>10 kg) and

CP710, *Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference - CEC, Vol. 49,* edited by J. Waynert et al.

do not provide continuous cooling. We present in this paper a design of MADR with a continuous operating mode. The design is based on miniature shielded superconducting magnets and on reliable magnetoresistive heat switches.

CONFIGURATION AND OBJECTIVES

Our goal is to realize a MADR which can provide continuous cooling at 50 mK from a 5 K reservoir. In our design, several stages of ADR are implemented in series in order to reach the desired temperature. As in [2] and [3], the temperature of the last (coldest) pill is kept constant by an accurate control of its magnetization and demagnetization rate. During the magnetization, the adjacent pill provides cooling to regulate the temperature. The possibility of recycling the pills regularly allows for a reduction in the size of the ADR: the faster we cycle, the less heat must be extracted by the paramagnetic pills and hence the smaller the pills have to be. The cycling frequency is limited mostly by eddy current heating that increases with the speed of ramping the magnets. Our design aims at obtaining the fastest cycle possible without substantially reducing the efficiency, in order to reduce the size of the pills.

The different components of MADR have been developed with a focus on reduction in size and fast cycling rate. We designed small paramagnetic pills with high heat conductivity. We also developed heat switches with a short switching time and high thermal performance. Finally, we assembled a single-stage MADR(FIGURE 1.a). These steps helped us grasp the research needed for the full prototype and validated our

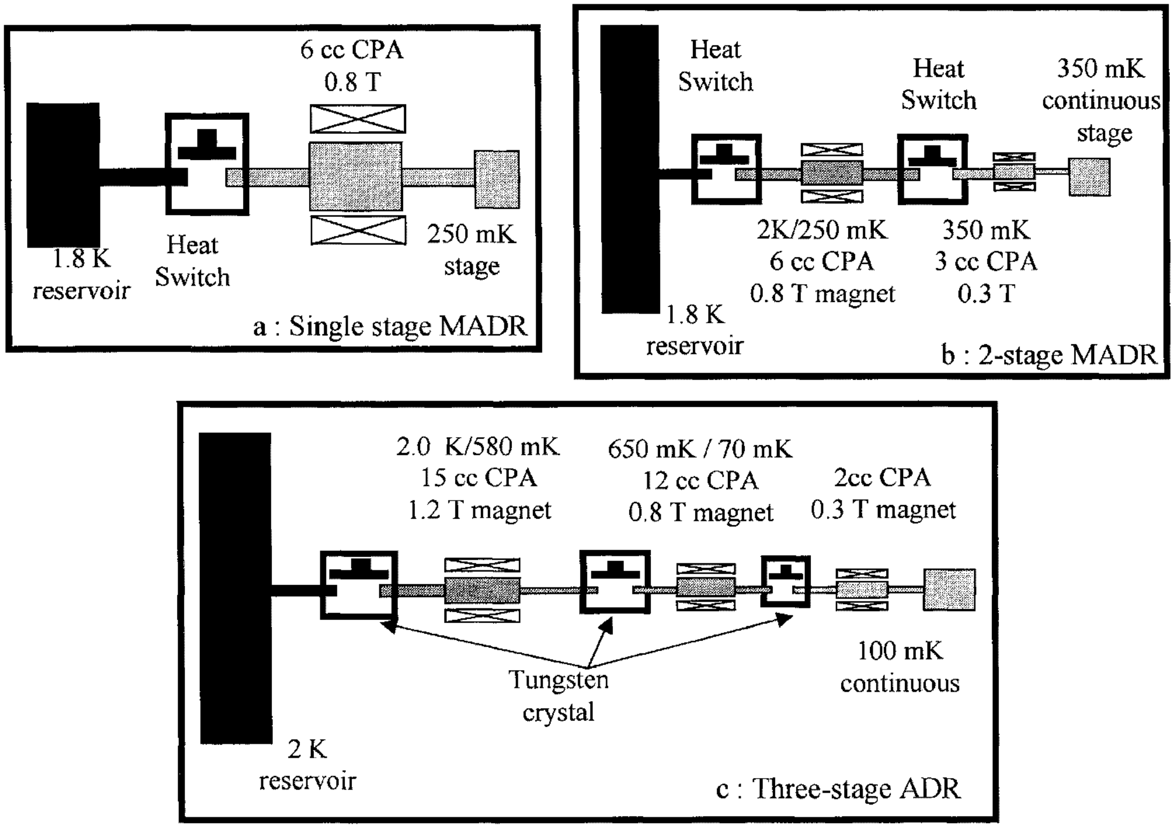

FIGURE 1. Several configurations for MADR. a : Single-stage. b : Two-stage. c : Three-stage.

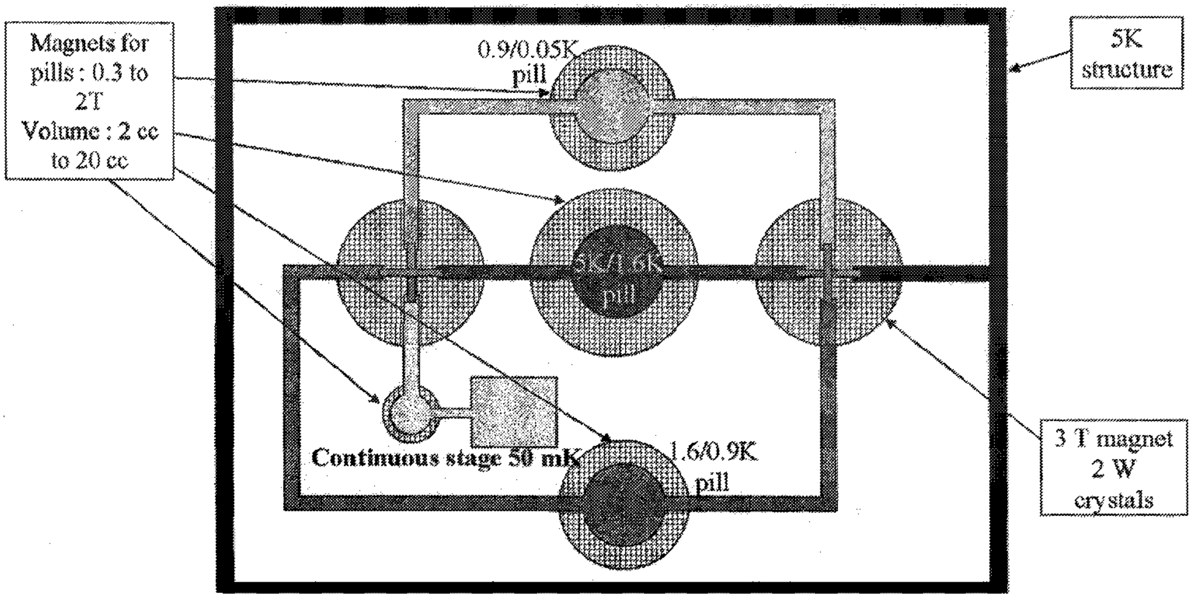

FIGURE 2. Schematic of a four-stage MADR. Does not fully represent structure.

approach. The realization of a continuous two-stage MADR(FIGURE 1.b) is on its way, and the next step will be to implement a third stage in order to achieve 2 K - 100 mK operation(FIGURE 1.c). Finally, we present in FIGURE 2 a schematic of a possible setup for a four-stage MADR. For the four stages, we expect to use magnetoresistive heat switches which can be grouped in pairs in order to reduce the size and mass of MADR. The structure will use nested copper plates suspended from each other by kevlar cords in a manner that constrains all 6 of their degrees of freedom [4]. The mass of the prototype will be less than 5 kg.

PARAMAGNETIC PILLS

For the stages operating under 2 K, chromic potassium alum (CPA) is used as the paramagnetic substance. It has long been used for ADRs that operate under 100 mK. It has advantages over other paramagnetic salts like ferric ammonium alum (FAA) such as a high decomposition temperature (89 °C) and being less corrosive, especially with copper. Since it is a salt of hydration, it must be maintained in a hermetically sealed container to avoid dehydration, which spoils its cooling capabilities. These issues are addressed in the salt pill design as follows. Copper wires are vacuum brazed on a copper sheet of the cold stage. Then, a thin brass "can" is soldered around these wires and the CPA salt pill is grown directly inside as in [5]. After growth, the can is closed with a thin brass lid and hermetically sealed with Stycast 2850 GT epoxy. Because the wires are embedded inside the CPA crystal, they make excellent thermal contact with the salt. We checked experimentally that the thermal conductivity between the pills and the copper bus is more than 6 mW/K at 200 mK, and is therefore not a limiting factor for our design (the heat conductivity expected for the switch being less than 1 mW/K at this temperature). We calculated that eddy current heating is negligible in this structure for the ramping speed discussed below. For the highest-temperature stage of the four-stage MADR we expect to use a paramagnetic material more suitable for this range of temperature like gadolinium gallium garnet (GGG).

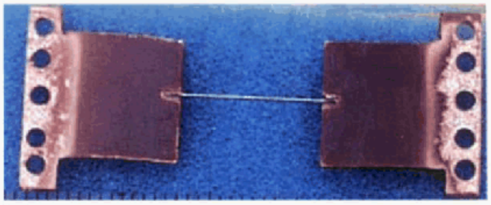

FIGURE 3. Magnetoresistive heat switch: a single crystal of tungsten is vacuum brazed to two copper thermal busses. The crystal diameter is 0.5 mm and length is 25 mm. Brazing alloy is 82% Gold and 18% Nickel.

CHOICE OF HEAT SWITCHES

We chose to use magnetoresistive heat switches because of their simplicity, reliability and short switching time[6]. These switches require superconducting magnets providing a field of several Teslas (see next section). Thanks to their wide temperature range of utilization, they can be used for all four of the switches needed in the four-stage MADR, simplifying our design as is described above. We have built and tested three magnetoresistive heat switches with tungsten crystal. We have improved upon our first tests of the thermal conductivity of a single crystal of tungsten by using, as in [7], a vacuum brazing technique for thermally connecting it to the rest of the MADR (FIGURE 3) circuit.

FIGURE 4 shows the measured thermal conductivity of the tungsten switch as a function of applied magnetic field for temperatures in the 2 - 10 K range. For the "off" conductivity, this data matches measurements made by [8]. The "on" conductivity measured is much lower than what was expected. As suggested in [7], we believe that this limitation is due to a size effect, the width of our crystal being smaller than the mean free path of the electrons in the crystal . This hypothesis is under investigation

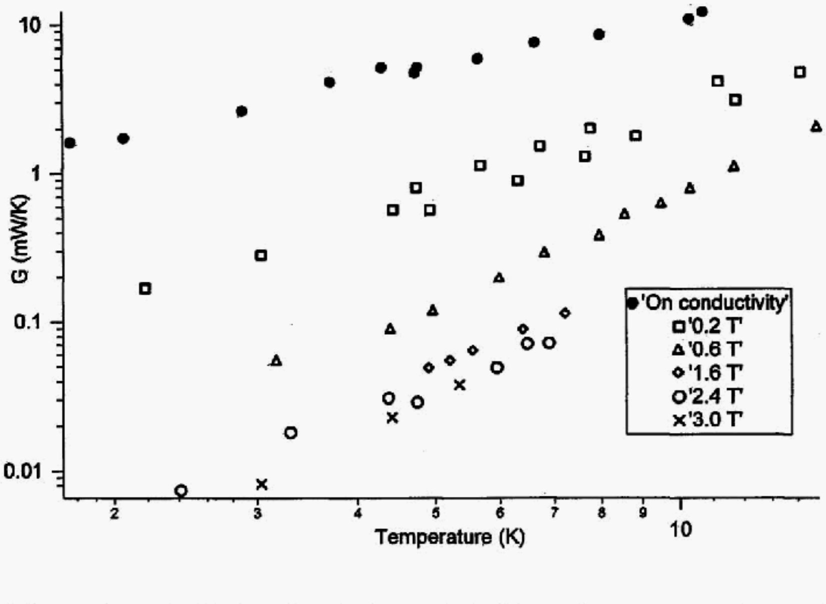

FIGURE 4. Thermal conductivity of a single crystal of tungsten as a function of temperature and applied magnetic field. The temperature represents the average temperature between the two sides of the crystal. The measurements are made at a base temperature of 2 K and 4 K. Measurements at lower temperature are planned.

by measuring the heat conductivity of crystals of bigger cross section.

MAGNETS

Superconducting magnets are required both for the paramagnetic pills and for the magnetoresistive heat switches. Each magnet has to be shielded in order to limit the parasitic magnetic field on the detectors and on the neighboring heat switches or pills. The magnets and especially their shields are responsible for most of the mass and volume of MADR. Moreover, the electrical power dissipated in the magnets is an important part of the total power required by the cooler. Designing the magnet has therefore been an important part of the project. We worked with the magnet/shield code POISSON[9] to optimize the design of the compact magnet and shield. After purchasing several small commercial magnets[10], we constructed our own in order to speed delivery and ease modifications. We have tried to minimize the size of the magnet while keeping the current below 15 A for each magnet. We wind 0.008" diameter multifilamentary NbTi wire [11] on a stainless steel bobbin, suitable for conduction cooling in a vacuum. The first magnet shields were made of vanadium permendur, as in [4] because of its high saturation induction (2.4 T). Despite its slightly lower saturation induction, we switched to silicon iron in order to limit cost and simplify machining. For the heat switch magnets, which require high field and small volume, we used two split solenoids with holmium cores placed end-to-end. Holmium is used as a flux concentrator because of its high saturation field (4 T). It has previously been used for field enhancement in similar superconducting magnets [12]. For the commercial magnet as well as for our homemade one, the field at the center of the magnet agrees with our calculations (FIGURE 5). According to our calculation, the use of holmium core increases the field

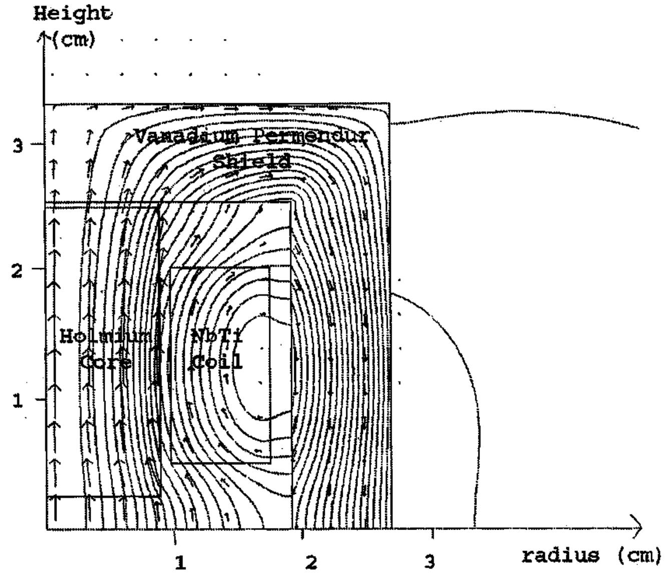

FIGURE 5. Simulation of magnetic field in split-coil superconducting magnet and shields. Figure shows upper right quadrant of geometry which is cylindrically symmetric about vertical axis. Horizontal midplane is location of the tungsten crystal for the heat switch; the magnet/shield achieves 3 T there with 15 A applied current. Leakage field is lower than 0.01 T at 5 cm from center. Directions of magnetic field lines are shown.

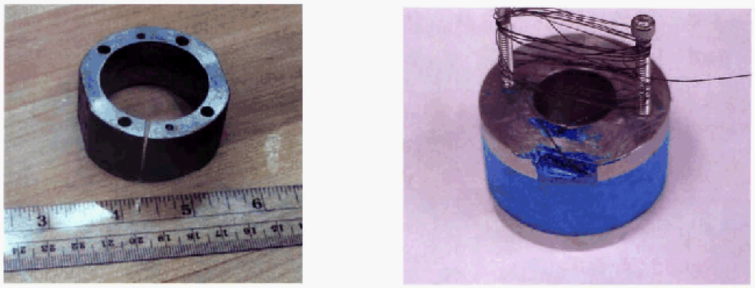

FIGURE 6. Miniature split-coil superconducting magnet for heat switch. The bore diameter is 1.5 cm. (Left) : Side magnet shield. In order to reduce eddy current heating in the magnet, a slot has been machined in the shield. (Right) : Coil.

by more than 50 % (2.2 T to 3.2 T in the middle). The heat switch magnets, including shield and core (FIGURE 6) have a mass of 600 g and a volume of 120 cm^3.

For the magnet for the paramagnetic pill, which require smaller fields in a bigger volume, only one solenoid is used, without a holmium core, in order to maximize the available space. Stray fields at the position of the 0.1 K stage are below 0.01 T. We expect to use superconducting shielding in order to reduce this value to below 0.1 mT.

CYCLING PERIOD AND EDDY CURRENT HEATING

The cycling period is linked to the size of the salt pills, the nominal power of the cooler and the refrigerator efficiency. The time of ramping the magnets has to be kept much shorter than the total cycle time in order to keep a long time for the heat transfer and hence reduce the power and the temperature gradient across the tungsten crystal while in the "on" state. Reducing the magnet ramping time increases the eddy current heating, both in the magnets and in the cold structure (mainly the copper thermal busses). Heating in the magnets themselves can quench the magnet, and decrease the overall efficiency of the cooler. Eddy currents in the copper busses that lead to the tungsten crystal or to the pills reduce the efficiency of each stage, increasing the power requirements and necessary size of the higher temperature stages. For our design, eddy currents are mainly due to the ramping of the magnets for the heat switches since the maximum field is larger than for the pills.

We found that a switching time of 30 seconds could be achieved. We measured an energy dissipation in the magnet of less than 1.5 J per cycle. For all the magnets of the four-stage, it will represent an average power of less than 10 mW on the 5 K reservoir. The heating by eddy currents in the copper bus has also been experimentally evaluated and we found that for a copper bus of 1 mm thickness and 20 mm width, the heating is approximately 0.5 mJ per cycle. This heating is negligible for all but the lowest temperature stage, where the two ramps of the switch would contribute to an average power on the cold stage of around 2 μW which would reduce the stage efficiency by around 10 %. For a cycling time of 500 s the ramping time of the switch would therefore be less than 15 % of the total time, which is satisfactory.

SIMULATION AND MAGNET CONTROL

In order to more accurately design a MADR, to predict its cooling power and also to help determine a control algorithm of MADR, we are developing a computer simulation of the prototype. This simulation includes a model of the salt pills, the conductivity of the heat switch as measured, as well as heating from eddy currents. Eddy currents are taken into account as a coefficient dependant on the derivative of the field and were evaluated experimentally. Losses from heat conductivity of the structure are also taken into account. We show in FIGURE 7 a typical cycle of a two-stage version of MADR as determined by our simulation.

We have built a temperature control system for the single pill ADR running in the lab now. It uses a commercial programmable power supply that is controlled by a PID loop [13]. The temperatures of the various stages are measured with ruthenium oxide thermometers read out through a commercial resistance bridge. A controller to cycle the six magnets for the refrigerators and heat switches simultaneously is being developed.

RESULTS AND CONCLUSION

We designed a light and compact four-stage MADR for continuous operation under 100 mK. A magnetoresistive heat switch based on a tungsten crystal has been designed and its conductivity has been measured. Brazing techniques for the crystal and for copper wires in the pills have been successfully used. We built a single-stage test MADR which proved the feasibility of the design and of the temperature control technique. We

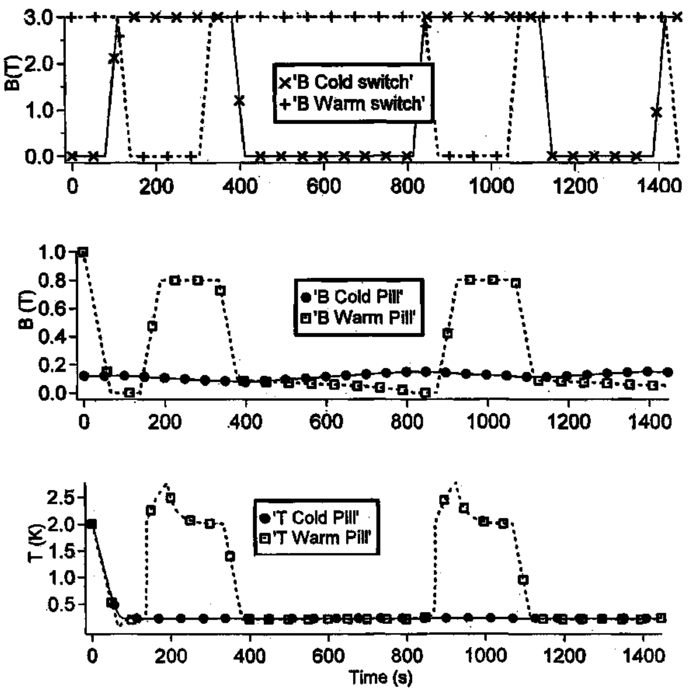

FIGURE 7. Simulation of a two-stage MADR. Top : Heat switch magnetic fields. Middle : Salt pill magnetic fields. Bottom : Salt pill temperatures. The continuous temperature stage is cooled from 2 K in the first cycle and regulated at 300 mK in the second cycle.

are now working on the implementation of three more stages.

ACKNOWLEDGMENTS

This work is supported by NASA grant NAG5-10204.

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