Automated temperature regulation system for adiabatic demagnetization refrigerators

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A temperature control system was constructed for an adiabatic demagnetization refrigerator operating between 50 mK and 4 K. The control algorithm is discussed and the system performance is presented. A temperature stability of 2 μK RMS at 100 mK has been maintained for more than 8 h. To improve the thermodynamic efficiency, the magnetic field is used as the control parameter, rather than resistive heating.

Keywords: magnetic refrigerator; adiabatic demagnetization refrigerator; temperature regulation

There has been much recent development of infrared bolometers[1,2] and X-ray microcalorimeters[3–5] designed to operate in the 100 mK regime. These highly sensitive detectors are particularly well suited for astronomical observations which require space-based platforms. Since adiabatic demagnetization refrigerators (ADRs) are capable of attaining 100 mK in a zero-*g* environment, we have produced an ADR system which demonstrates the ruggedness, compactness, automated operation, high thermodynamic efficiency and long hold time desired for space-based operation[6].

Because bolometers and calorimeters are thermal detectors, a very stable heat sink temperature is required. To maintain an energy resolution of 1 part in 1000, a typical X-ray microcalorimeter requires a cold stage stable to 8 μK at 100 mK[7]. Requirements for infrared bolometers are similar, depending on the observing mode and circuit design. We describe here an ADR temperature regulation system which maintains this level of stability by controlling the refrigerator magnetic field, rather than the less efficient method of using Joule heating to maintain a cold stage above the unregulated refrigerator temperature.

We have chosen to put the feedback under computer control, although the regulation of a magnetic refrigerator has been accomplished previously without the use of a computer[8]. This allows us the flexibility to change feedback algorithms easily, to detect and remove cosmic ray-induced noise, to optimize control parameters for different temperatures and, if desired, to automate completely the refrigeration cycle. The resulting system is extremely useful for laboratory measurements in the 50 mK–4 K range and for testing techniques to be used in space.

System design

A block diagram of the temperature regulation system is shown in *Figure 1*. The cold stage is in close thermal contact with ≈ 40 g of the paramagnetic salt iron(III) ammonium alum. The salt is suspended in the bore of a superconducting solenoid which generates its rated field of 3 T at a current of 5.6 A. The magnet current is sup-

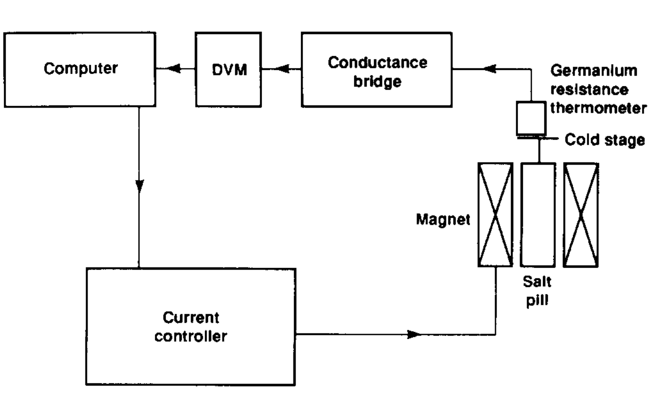

Figure 1 Block diagram of the adiabatic demagnetization refrigerator control system

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plied either by a standard, manually controlled 6 A supply or by a computer-controllable 0.6 A supply of our own design. The temperature of the cold stage is measured by a Lakeshore Cryotronics GRT-200A-30 germanium resistance thermometer. The thermistor is read with a Biomagnetic Technologies (BTi) Model 1000 conductance bridge. An HP 3478A 5½ digit DVM reads the analog output of the conductance bridge since the 4½ digit DVM in the BTi bridge is not sufficiently precise for our purposes.

An IBM PS/2 computer controls the feedback. The computer reads the DVM via a GPIB bus, and converts the bridge voltage to a cold-stage temperature. Using the algorithm outlined below, the computer determines the desired ramp rate for the magnet current. This ramp rate is then programmed into a current supply of our own design. Computer control of the ramp rate rather than the magnitude of the current is preferable for several reasons: first, it is the current ramp rate $\dot{I}$, rather than the current I, which determines the cooling power, and is thus analogous to the power in a traditional Joule heating temperature regulation system. A key difference however, is that $\dot{I}$, unlike the Joule power, may change signs, which adds versatility to the controller, but increases the possibility of oscillation. In a stable configuration, it is $\dot{I}$ rather than I which is nearly constant; the computer need only update the ramp rate several times per minute, whereas I may change bits many times per second. This frees the computer for other tasks, and removes time-critical functions from the computer. Additionally, accidental large changes in current are avoided.

The current controller must be capable of producing a precise current ramp over periods of 24 h or longer, which would be extremely difficult using an analog ramp generator. We have instead opted to split the current controller into digital and analog sections. The analog portion produces a current proportional to the value of a 16-bit register maintained in the digital section. The value of this register can be read by the PS/2 computer, but not directly altered. The register value can be held constant, or ramped in either direction. The ramp rate can be set from 1.3 ms to 10 s per bit with 10 μs precision. The ramp rate and direction can be set either manually or by computer control. The manual mode is useful for cycling the refrigerator and for coarsely maintaining a temperature without use of the computer. The analog section of the current supply provides extremely low ripple current to a highly inductive load, and will safely manage a magnet quench. The computer interface contains flags indicating zero, full scale or a magnet quench.

In the absence of noise or time delays, the time history of the cold stage temperature under optimum regulation would be a sawtooth function: an upward drift in temperature due to heat leak at fixed H, followed by an adiabatic decrease in T as the magnet current is reduced by one bit. For adiabatic temperature changes, we have approximately $T \propto H \propto I$ over most of the operating range. This implies a step height of 100 mK divided by 2^{16} steps = 1.5 μK per step (with the current near full scale). In actuality, thermal and electrical time constants in our system smooth the sawtooth over several seconds. A careful control of the rate of current change can then provide better stability than this step height would suggest. For a 24 h hold time, the 16-bit controller will flip an average of 1 bit every 1.3 s.

Feedback algorithm

Variations in the temperature of the cold stage should be described by

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\dot{Q}}{C_H} + \left.\frac{\partial T}{\partial H}\right|_S \frac{\mathrm{d}H}{\mathrm{d}t} \tag{1}$$

where $\dot{Q}$ is a slowly varying heat leak into the system, H is the magnetic field (proportional to current) and C_H is the specific heat of the salt pill at constant field. If T_i and I_i are the temperature and current at time $i\Delta t$, then Equation (1) may be rewritten as

$$\frac{1}{\Delta t}(I_i - I_{i-1}) = a + \frac{c}{\Delta t}(T_i - T_{i-1}) \tag{2}$$

where a and c are slowly varying parameters. We would like our algorithm to determine a and c by fitting the linear Equation (2) to an appropriately weighted set of recent measurements T_i and I_i, with a and c as unknowns. A problem with this adaptive algorithm, however, is that when the regulation is successful, the $(T_i - T_{i-1})$ term in Equation (2) consists solely of readout noise. In this case, the parameter c becomes poorly determined, and the algorithm becomes unstable.

We use an alternative method, in which the value of c is fixed by assuming that $\partial T/\partial H|_S = T/H$. This is a good approximation provided that H is not too small. The drift rate parameter a is allowed to vary slowly to reflect changes in $\dot{Q}$ and C_H. Letting $\dot{I}_i$ be the current ramp rate set at time $i\Delta t$, we calculate at each time step

$$a_{\mathrm{obs}} = \dot{I}_{i-1} - \frac{c}{\Delta t}(T_i - T_{i-1}) \tag{3}$$

The best estimate of a is updated at each step by averaging the latest a_{obs} with the previous estimate:

$$a_i = \left(1 - \frac{\Delta t}{\tau}\right)a_{i-1} + \frac{\Delta t}{\tau}a_{\mathrm{obs}} \tag{4}$$

where τ is a preset time constant. The new ramp rate is then chosen to move the temperature to the set point by the next time step:

$$\dot{I}_i = a_i + \frac{c}{\Delta t}(T_{\mathrm{set}} - T_i) \tag{5}$$

Equations (3)–(5) define the basic feedback algorithm. This single-parameter adaptive algorithm is mathematically equivalent to a proportional + integral (PI) linear controller, with

$$\dot{I}_i = -\frac{c}{\Delta t}\left[(T_i - T_{\mathrm{set}}) + \frac{\Delta t}{\tau}\sum_{j=0}^{\infty}(T_{i-j} - T_{\mathrm{set}})\right] \tag{6}$$

Use of the computer for feedback allows easy changes to this PI algorithm. Cosmic rays and electrical noise spikes can often cause sudden changes in the thermistor reading which are not indicative of true temperature changes. Our algorithm checks for such sudden large changes in temperature readout, and waits for the readout to recover before updating $\dot{I}$.

A short averaging period τ allows more rapid convergence to a new set point. A longer value of τ, however, allows many temperature readings to contribute to the determination of a. In the presence of an RMS readout noise δT on each T_i, this averaging will reduce the noise-induced error in the parameter a_i, and hence allow reduction of fluctuations in the ramp rate $\dot{I}_i$ and in the true cold-stage temperature. Our feedback algorithm uses a short τ until the set point is closely approached, then switches to a longer τ when near equilibrium. When $\tau \gg \Delta t$ and our approximation for c is good, the expected variance in temperature readings is $\sqrt{2}\delta T$. The variance in the actual temperature of the cold stage should be δT. By changing our algorithm somewhat, we could reduce the cold-stage temperature fluctuation below the readout noise δT. The ultimate limitations of such a system have been discussed by Kittel[9].

Performance

This control system has been successfully utilized on three different refrigerators. The demagnetization cycle starts with the salt pill at 1.8 K, and the 6 A supply is used to magnetize the salt pill isothermally to 3 T. The salt pill is then isolated from the 1.8 K bath and the field is ramped to zero over several minutes, reaching a temperature well below the 50 mK limit of our thermometry. The 6 A supply is then disconnected from the solenoid, and the computer-controllable 0.6 A supply is connected. The current is then ramped up to bring the temperature near the desired set point, initial values are assigned to a and c, and the feedback system is activated. A segment of an 11 h record of the heat sink temperature readings under regulation is shown in *Figure 2*. The relevant parameters for these data are $T_{set} = 0.1$ K, $\Delta t = 10$ s, $\tau = 300$ s, $a = -0.3$ bits s^{-1}, corresponding to $\dot{Q} \approx 0.2$ μW, and the time constant of the conductance bridge is 10 s.

Excluding the first 15 min in which the system was stabilizing, the RMS deviation of the temperature reading from the set point is 1.9 μK, or 2 parts in 10^{-5}. The noise level of the BTi conductance bridge is specified to be $\delta T = 1.0$ μK, so we expect an RMS readout fluctuation of 1.4 μK, not far from that observed. The short-

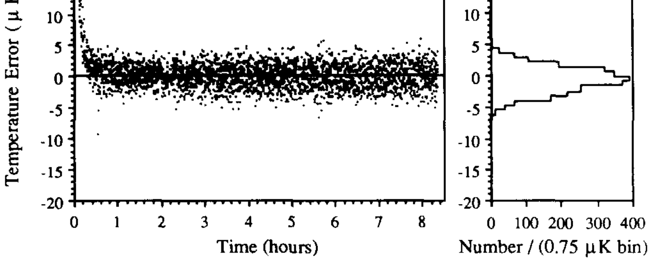

Figure 2 Temperature stability of the adiabatic demagnetization refrigeration system operating at 0.1 K. The RMS spread in temperature is 2 μK within an 8 h interval beginning 15 min after the temperature feedback system is initialized

term temperature stability of the cold stage is limited by thermometer readout noise. This could be improved by installing a low-noise JFET preamplifier in the Dewar vessel to read the thermistor, and by using a thermistor with a steeper temperature dependence. We would expect to be able to reduce short-term fluctuations to a few tenths of 1 μK before the discrete steps in the 16-bit current controller become a limitation.

The long-term stability of the temperature is at present limited by the $\approx 0.6\%$ per month drift in the gain of the BTi conductance bridge. To remove the effects of gain variations, the thermistor could be placed in a Wheatstone bridge with cold fixed resistors in the other arms. This, however, would sacrifice the present ability to change set points at will.

Conclusion

We have stabilized the temperature of our adiabatic demagnetization refrigerator to 2 μK at 100 mK without the use of Joule heating. The stability is at present limited by the noise level of the temperature readout system, and could probably be improved by a factor of ten if desired by changing the readout electronics. The use of a computer in the feedback loop allows easy use of techniques such as cosmic ray detection and adaptive control algorithms. In the laboratory, the system permits rapid attainment of stable temperatures from 50 mK to 4 K. The inclusion of the ramp generator in the current supply removes time-critical functions from the computer, so that computing resources can be shared with other instruments.

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