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Nuclear Instruments and Methods in Physics Research A 559 (2006) 657–659

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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# Advanced adiabatic demagnetization refrigerators' temperature control system

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Available online 5 January 2006

**Abstract**

We will present a temperature control system for advanced adiabatic demagnetization refrigerators (AADRs). Advanced X-ray and IR detectors, which need to be cooled to temperature below 100 mK, are driving many developments in AADRs. AADRs have many advantages and are used for ground testing of detectors, as well as enabling commercial applications including semiconductor microanalysis, macromolecule spectrometry, and neutron radiation detectors. AADRs include two stages, double stage and continuous stage ADRs. These systems can use multiple paramagnetic salts within the same magnet, or multiple salt-pill/magnet stages. The present state-of-the-art has focused on component development and not integrated control systems, however, temperature control is critical for real-time analysis and maintaining the X-ray line positions. In the control system we will present, temperature and cycle control is based on feedback control of the voltage (or current ramp rate) across the magnet(s). The most complex system is a continuous ADR. This requires temperature monitoring and magnet control of four salt-pill stages and four heat switches. Additionally, the timing of the cycle is critical for continuous cooling. This control system will have four magnet power supplies, two dedicated low-temperature thermometry channels, and a four-channel mux-circuit. Control update rate will be 10 Hz. Two of the four magnet power supplies will be 5 A/5 V current sources, which can be used in series to control a single 10 A/5 V magnet. Software control, cycle timing and thermometry will be discussed.



*PACS:* 84.30.−r

*Keywords:* Adiabatic demagnetization refrigerator; Magnetic refrigeration; Low temperature

## 1. Introduction

Improvements in adiabatic demagnetization refrigerators (ADRs) have been driven by the cryogenic requirements for new IR and X-ray detectors [1] including cooling to below 100 mK, working in micro-gravity, low mass and high efficiency. These advantages also enable ground-based applications including X-ray material analysis.

These detectors require high-resolution temperature control for maintaining X-ray line positions. To address this, an integrated control system is being developed. This includes, in a single enclosure, temperature measurement, magnet power supplies, and cycle control software for temperature stability and complete AADR cycle control.

## 2. Advanced adiabatic demagnetization refrigerators (AADRs)

The basic ADR is a paramagnetic salt, magnet, and heat switch connected to a thermal bath. The cooling cycle is isothermal magnetization followed by an adiabatic demagnetization. Typical operation involves an isothermal demagnetization to maintain a constant temperature.

A two-staged ADR [2] is operationally similar to a single stage. The key difference is the inclusion of two paramagnetic salts within the same magnet. One salt acts as a thermal buffer to the other salt. A double stage ADR [3] is two separate salt-pill stages: two salt pills with two magnets and a heat switch between stages. The upper temperature stage pre-cools the lower temperature stages. Both systems improve the hold time at temperature and reduce total magnet size while enabling a 4.2 K start temperature.

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0168-9002/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2005.12.096

A continuous ADR (CADR) [4] is four independent stages that are continuously cycled. The lowest temperature stage is controlled at a fixed temperature. When the entropy capacity of this stage is low, the next higher temperature Stage (Stage 2) is demagnetized to a temperature below Stage 1, the heat switch between them is turned on, and then Stage 1 is isothermally magnetized as Stage 2 absorbs the heat from Stage 1. Stage 2 then cascades its heat to the higher temperature stages. The CADR can provide continuous cooling at modest cooling powers.

## 3. Continuous ADR controller design

The temperature of an ADR stage is regulated by controlling the demagnetization rate. This can be done by closed-loop control of the voltage across the magnet or controlling the ramp rate of a current source. Control stability depends on the temperature measurement resolution, setting resolution of the power supplies, and thermal response time of the salt-pill stage.

### *3.1. Thermometry*

Ultra-low-temperature thermometry requires low excitations to minimize self-heating errors. To achieve acceptable measurement resolution, an AC bridge is typically used. However, an AC measurement is more expensive and complicated. To minimize board space and costs, we designed a DC measurement circuit. The small increase in self-heating is traded for circuit simplicity. An additional advantage is that it enables a faster sampling rate. Sampling of 10 Hz, with current reversing, is easily achievable.

The thermometry system is designed as two independent and identical channels, which are used to monitor Stages 1 and 2. An additional mux-circuit is designed to sample Stages 3, 4, and the base plate temperature. The lowest excitation for all measurements is 10 nA.

### *3.2. Magnet power supplies and heat switches*

This design includes four magnet power supplies. Two supplies are voltage sources with an 8 V/3 A output. The Stages 3 and 4 supplies are two current sources at 5 A. The setting resolution of all supplies is 18-bit, with a 10 Hz update rate. The dual current sources were chosen to enable parallel operation to 10 A for other AADRs.

The heat switches for the CADR are three passive gas-gap switches and an active superconducting switch. To activate the superconducting switch, a smaller ($I < 600$ mA) supply is designed.

### *3.3. Control system software*

The CADR has four independently controllable stages, with the action of each stage dependent on the conditions of the other stages. For software development we have modeled the system as a state machines. Conditional actions, such as recycling Stage 3 or activating the heat switch, are modeled at transitions between states. An example is in Fig. 1.

Stage 1 will be in continuous closed-loop control with the ability to change the voltage across the magnet to maintain temperature. This allows a fast (10 Hz) control loop. The cycle control system will monitor the current in the Stage 1 magnet. At a pre-determined level, this will

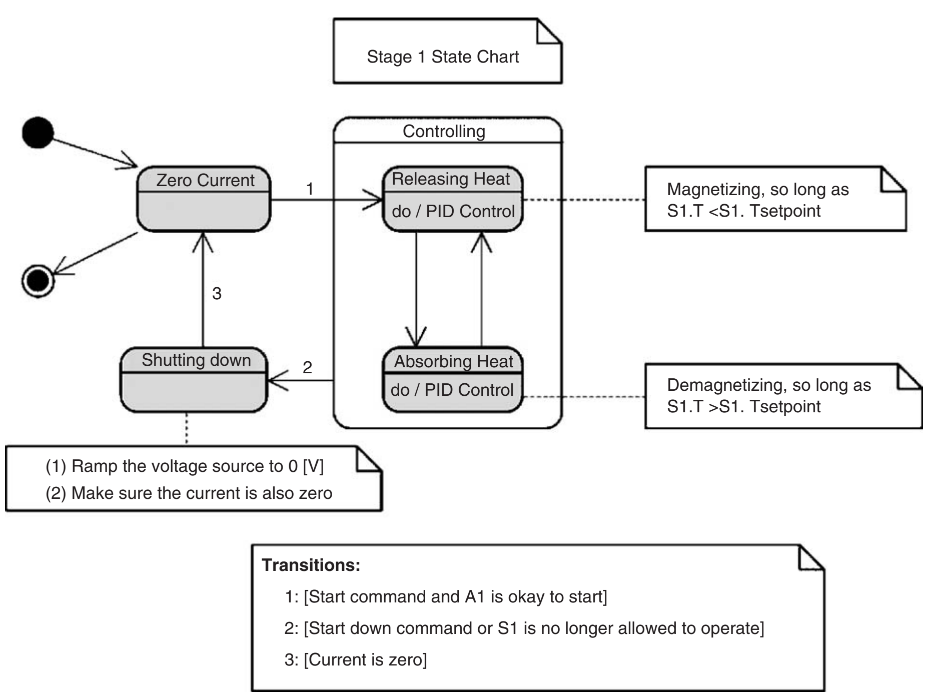


Fig. 1. Shows state machine model for Stage 1. Stage 1 continuously absorbs or releases heat to maintain temperature.

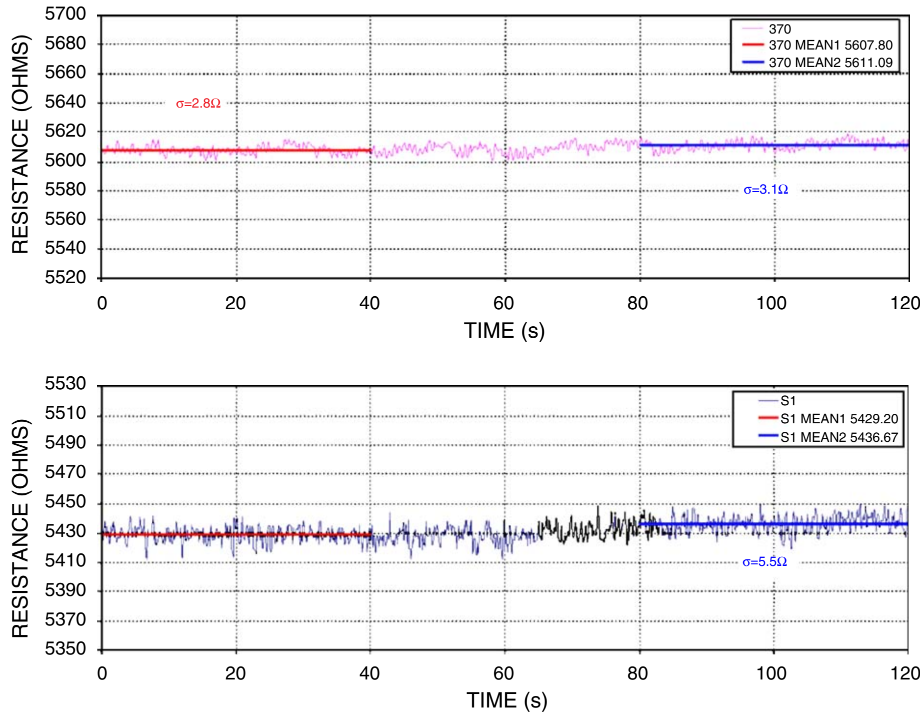


Fig. 2. Shows a comparison between DC design and AC resistance bridge. Both instruments monitoring ruthenium oxide sensor at 50 mK.

cause a transition in Stage 2. It will trigger Stage 2 to go to a temperature lower than Stage 1 and change the heat switch between them to the conducting state. As the heat load changes, the Stage 1 tight temperature control loop will respond by magnetizing to maintain temperature.

The software design is currently on an independent PC platform, which will have a GUI interface and Ethernet connectivity.

## 4. Results

The DC measurement circuit has been tested. A ruthenium oxide sensor, with a nominal resistance of 6000 Ω at 50 mK, was measured and compared to the calibrated values (Fig. 2). The self-heating offset at 10 nA was less than 0.15 mK, and was less than 2 mK with a 30 nA excitation.

The resistance resolution was $\pm 5.5\,\Omega$ at 10 Hz sampling. With the $\mathrm{d}R/\mathrm{d}T$ of the sensor, this corresponds to a temperature sensitivity of 100 μK. Averaging for 1 s improves the resolution to $\pm 1.8\,\Omega$ or $\sim\pm 35\,\mu$K. Using a sensor with larger $\mathrm{d}R/\mathrm{d}T$ would improve this further. If necessary and if a self-heating offset of 1–2 mK was acceptable, then a 30 nA excitation could be used to improve temperature resolution.

The thermometry measurement system is to the level where testing on a CADR is required for further developments.

Power supplies are being developed. The software is presently being coded, after which testing on a complete CADR system will begin.

## 5. Conclusions

Development and testing of a CADR control system is ongoing. This work can be applied to other systems, including a two stage ADR. This will lead to a control system that will better enable detector-based applications.

## Acknowledgments

This work has been supported by NASA SBIR Phase II Award no. NNG04CA36C.

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