INNOVATIVE TECHNIQUES FOR X-RAY CALORIMETRY

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ABSTRACT. In our x-ray calorimetry effort, we have developed several techniques which may be helpful to other groups working in this field. We are studying several different monolithic and composite calorimeter designs. In our readout configuration, the preamplifier circuit employs negative voltage feedback which allows us to accurately measure the temporal profile of the thermal pulse produced by an x-ray absorbed in a micro-calorimeter. Rise times of less than two microseconds have been observed in monolithic devices operating at .3 K. Furthermore, the feedback preamplifier can be configured for either positive or negative electro-thermal feedback. This preamplifier system is followed by an analog pulse shaping amplifier with a frequency response that can be adjusted to yield the maximum signal to noise ratio for a given thermal response of the calorimeter. In addition, we have developed several diagnostic procedures which have been useful in determining the operating and noise characteristics of our devices. These include an infrared light-emitting diode which flashes a discrete amount of energy on to the calorimeter, and a capacitively coupled test input to the preamplifier which allows us to directly determine the total noise in the thermal detection system. Finally, we are developing an adiabatic demagnetization refrigerator with a temperature control system that is designed to stabilize the 0.1 K cold stage to better than 8 μK. This is required for a resistive thermal detector with resolving power of 1000.

1. INTRODUCTION

Cryogenic x-ray calorimeters are of great interest to x-ray astronomy because they offer high resolving power with nearly 100% quantum efficiency below 10 keV. X-ray spectroscopy with microcalorimeters was first discussed by Moseley *et al.* (1984) of Goddard Space Flight Center (GSFC) and tested by McCammon *et al.* (1984) of Wisconsin. The collaboration between GFSC and Wisconsin has been steadily progressing toward the goal of practical high resolution x-ray calorimeters. They have measured a resolution of 17 eV (Moseley *et al.* 1988), and have plans to use such a device in a upcoming sounding rocket experiment (Zhang and McCammon, 1988) Additional research has been reported by Coron *et al.* (1985) and Fraser (1987). In October 1986, the Laboratory for Experimental Astrophysics initiated a program to develop x-ray microcalorimeters. This paper describes some of the techniques we have developed with emphasis on those which may be of use to other groups working in this field.

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2. ELECTRONICS AND DIAGNOSTICS

With practicality and high count rate capability in mind we have conceived of a new approach to low noise pulse counting electronics for microcalorimeters. The circuit configuration we have adopted is based upon JFET preamplifiers with negative voltage feedback that Goulding, Landis, and Pehl (1969) developed for use with silicon and germanium charge collecting detectors. Negative voltage feedback significantly improves the temporal response of the calorimeter over previous techniques, without adding any additional noise (Silver *et al.*, 1989). It has enabled us to measure the thermalization time of high resistance germanium calorimeters to be less than 1 μs . We hope to take advantage of this swift thermalization time and develop detectors that operate at high count rates (Silver *et al.*, 1988).

The negative voltage feedback amplifier also allows the calorimeter to be operated with either a constant voltage (V) across or a constant current (I) through the calorimeter. In the constant voltage mode, the calorimeter is placed at the input to the amplifier and a bypass capacitor holds the voltage constant while the calorimeter's resistance (R_C) undergoes quick excursions. This configuration is shown in Figure 1. When a photon strikes the calorimeter, its resistance drops. Since the voltage is held constant during this time, the biased induced heating (V^2/R_C) increases and the duration of the pulse is increased. The result is positive electro-thermal feedback. In contrast, the constant current configuration results in negative electro-thermal feedback since the bias heating (I^2R_C) drops when the calorimeter temperature rises. In the constant current case the calorimeter is placed within the feedback loop of the amplifier, as shown in Figure 2.

Our pre-amplifier configuration provides flexibility since it allows us to switch from constant voltage to constant current mode at any time during an experiment, without opening the cryostat. When quicker pulses are required, we switch to constant current mode with negative electro-thermal feedback. If longer pulses are preferred, then we can return to constant voltage mode.

The JFET we are currently using is the Interfet 2N6453 which has been preselected for noise less than 1 nV/√Hz at 300 K. This JFET is ensconced in plastic which helps reduce microphonics which originate when the drain lead inside the JFET moves relative to the gate lead. The total gate input capacitance is 15 pF and the drain voltage is set to 2.5 V. The drain current is held at 4 mA, which maintains the device near its 130°K optimal operating temperature. A small copper wire provides a thermal link between the JFET and the liquid nitrogen bath. This link has two beneficial effects. First, the 9 mW of power dissipated in the JFET flows into the nitrogen bath, thus extending the hold time of the cryostat. Secondly, the link to the liquid nitrogen bath prevents the JFET temperature from dropping to such a low temperature that it will not operate.

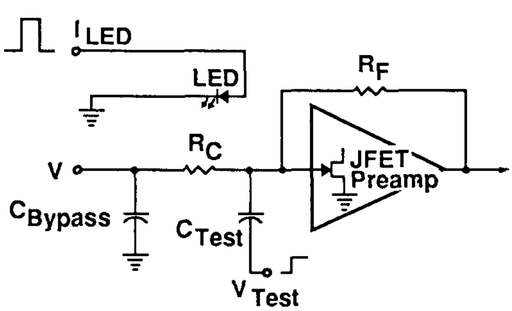

Fig. 1. The constant voltage preamplifier configuration is shown with test capacitor C_{TEST}, and infrared LED.

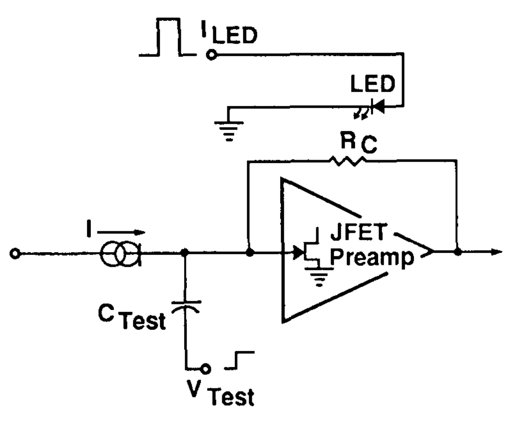

Fig. 2. The constant current preamplifier configuration.

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The preamplifier output is filtered and amplified by our analog pulse shaping post-amplifier. This filter system uses one differentiator and five integrators to limit the bandpass of the signal and noise. The time constant of this filter system can be adjusted to maximize the signal to noise ratio. The post-amplifier output is fed to a pulse height analyzer to obtain spectra. The post-amplifier is described in detail by Goulding and Landis (1982).

We have implemented several new techniques for diagnosing calorimeter performance. First, a test input capacitor (C_{TEST}) enables us to exercise the entire electronic chain without irradiating the calorimeter. This provides a combined measure of the electronic, Johnson, and phonon noise, independently of any "conversion noise" in the detector. This test input also allows us to measure the important time constants in the system. With the calorimeter in the feedback loop (constant current), the time constant $R_C C_C$ can be measured, where C_C is the intrinsic capacitance of the calorimeter. With the calorimeter out of the feedback loop (constant voltage), the time constant $R_F C_F$ can be measured, where C_F is the intrinsic capacitance of the feedback resistor R_F. Second, a controllable infrared LED is used to independently test the operation of the calorimeter. This LED produces short bursts of infrared light at regular intervals, which are absorbed by the calorimeter. These heat pulses are extremely useful for measuring the thermalization time, thermal decay time, and in conjunction with the thermal conductance obtained from the calorimeter load curve, the heat capacity. Both the infrared LED and the test input capacitor are shown in Figures 1 and 2.

One other useful laboratory technique we have been using is to locate our x-ray sources outside of the cryostat. This allows us to make spectra with a number of different sources, and at various count rates. It also allows us to remove the x-ray source and measure the total noise of the system in the absence of pulses. The photons enter the cryostat through a thin beryllium window which blocks the 300 K radiation, maintains the vacuum integrity of the cryostat, and passes x-rays with energies above 4 keV with nearly 100% efficiency. The photons then pass through thin aluminum foils located on the 77 K nitrogen shield, and the 1.5 K helium shield. The total distance from the source to the detector is only 5 cm.

3. ADIABATIC DEMAGNETIZATION REFRIGERATOR (ADR)

We have invested considerable effort in a parallel program to construct and test ADRs for use in the laboratory and eventually in space. Our system uses ferric ammonium sulfate as its paramagnetic salt. Two parts of the salt (by weight) are dissolved in one part 7% sulfuric acid solution held at 37°C. The crystal is then grown directly on a brush of gold wires which have been silver soldered into a copper post. Both the copper and the silver solder are plated with gold to prevent corrosion by the salt. The 2 cm diameter, 6 cm long salt crystal is then sealed with Stycast epoxy into a stainless steel cylinder which is supported in the magnet bore by twelve lengths of nylon monofilament each 4 cm long and .28 mm diameter. The measured heat leak of this system is about 0.2 μW when operated at 0.1 K. A temperature of less than 50 mK has been achieved and the hold time at 100 mK is more than 12 hours.

High resolution x-ray spectroscopy using microcalorimeters sets stringent bounds on the thermal stability of the refrigeration system. For example, if S is the voltage step produced by a photon of energy E absorbed by a calorimeter with a total heat capacity of C_V, then

$$S = I\Delta R = I\frac{dR}{dT}\frac{E}{C_V},$$

where I is the current (assumed to be constant in this example), ΔR is the change in calorimeter resistance and T is the temperature. If the dominant contribution to the calorimeter heat capacity is crystalline in origin, the Debye law predicts $C_V \propto T^3$. At the temperatures of interest, semiconductor resistors tend to vary as $R \propto e^{\sqrt{\Delta / T}}$. In this case

$$\frac{d\,\log|S|}{d\,\log T} = -\left[\frac{9}{2}+\frac{1}{2}\frac{\sqrt{\Delta}}{\sqrt{T}}\right] \cong \frac{T}{|S|}\frac{\delta S}{\delta T}.$$

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So for $S/\delta S > 1000$, a stability of $\delta T < 8\ \mu K$ is required for $\Delta = 25$ and $T = .1$ K.

To achieve this temperature stability, we have begun developing a microprocessor-based servo-control system that will adjust the superconducting magnet current to the desired precision. By controlling the temperature directly with the magnetic current, we avoid adding extra heat into the system that is characteristic of heater driven control systems. This extends the total hold time of the system, and reduces the mechanical complexity. A low resolution prototype of this controller has been tested, and a stability of +/– 20 μK has been already been achieved. We are confident that the new control system will surpass the required stability.

4. CONCLUSIONS

With high energy resolution, high quantum efficiency and a broad energy bandwidth, a practical x-ray calorimeter system would offer many advantages over solid state detectors and crystal spectrometers. The techniques described here have been useful in the development of x-ray calorimeters, and may be important in making practical devices. The negative voltage feedback amplifier allows fast signals to be processed which is essential if these detectors need to be used in moderate count rate applications. This electronic technique has already enabled us to study the intrinsic time response at temperatures below 1 K. With the constant current to constant voltage switching ability, a calorimeter can be designed so that resolution can be traded for speed at any time. Finally, the analog pulse processing is operationally straightforward, and the test pulse diagnostics provide direct ways of determining the system parameters.

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5. REFERENCES

Coron, N., Artzner, G., Dambier, G., Jegoudez, G., Leblanc, J., Lepeltier, J. P., Deschamps, J. Y., Rocchia, R., Tarrius, A., Testard, O., Hansen, P. G., Jonson, B., Ravn, H. L., Stroke, H. H., and Turlot, E. 1985, *Proc. of SPIE,* **567**, 389.

Fraser, G. W. 1987, *Nucl. Inst. Meth.,* **A256**, 553.

Goulding, F. S., Landis, D. A., and Pehl, R. H. 1969, in *Semiconductor Nuclear-Particle Detectors and Circuits*, ed. W. Brown, W. Higinbotham, G. Miller, and R. Chase (Washington, D.C.: National Academy of Sciences), p. 455.

Goulding, F. S. and Landis, D. A. 1982, *IEEE Trans. Nucl. Sci.,* **NS- 29**, 1125.

McCammon, D., Moseley, S. H., Mather, J. C., Mushotzky, R. F. 1984, *J. Appl. Phys.,* **56**, 1263.

Moseley, S. H., Mather, J. C., and McCammon, D. 1984, *J. Appl. Phys.,* **56**, 1257.

Moseley, S. H., Kelly, R. L., Schoelkopf, R. J., Szymkowiak, A. E., McCammon, D., and Zhang, J. 1988, *IEEE Trans. Nucl. Sci.,* **35**, 59.

Silver, E., Labov, S., Landis, D., Madden, N., Goulding, F., Beeman, J., Haller, E., Rutledge, J., Bernstein, G., and Timbie, P. 1988, *Proc. IAU 115*, this volume.

Silver, E., Labov, S., Goulding, F., Madden, N., Landis, D., and Beeman, J. 1989, *Nucl. Instr. Meth.*, submitted.

Zhang, J. and McCammon, D. 1988, *Proc. IAU 115*, this volume.

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