



Position-Sensitive Magnetic Calorimeters for *Lynx*

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Abstract

We describe the performance of position-sensitive metallic magnetic calorimeter X-ray detectors for potential future astrophysics missions, such as *Lynx*. The motivation behind this is to achieve a large focal plane area by increasing the number of pixels compared to the number of readout channels (called *hydra*). The detector consists of a 5×5 array of gold absorbers thermally coupled to a paramagnetic sensor. Since each absorber has a different thermal link to the sensor, it generates a different pulse shape and enables discrimination of pixel position. Recently, we have been successfully able to discriminate 25 averaged pulse shapes by means of rise-time and pulse height. The measured pulse shapes and distribution agree well with the modeling results. The estimated energy resolutions based on the pulse height and noise data we measured are 2.8–3.7 eV for MnK α X-ray photons at 50 mK.

Keywords Magnetic calorimeters · Position-sensitive detector · *Hydra* · *Lynx*

1 Introduction

Lynx is an X-ray telescope mission, which is one of the four mission concepts for NASA's 2020 Astrophysics Decadal Survey. *Lynx* is a successor to the *Chandra* X-ray Observatory and aims to retain a high angular resolution of < 1 arcsec, a large detection area of 5×5 arcmin² field-of-view and an energy resolution of < 3 eV FWHM for X-rays in the energy range 0.2–7 keV.

One of the detector technologies under consideration for the *Lynx* X-ray Microcalorimeter (LXM) is the metallic magnetic calorimeter (MMC) [1]. MMCs

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have demonstrated a energy resolution of $\Delta E = 1.58$ eV FWHM at 6 keV [2]. MMC is an equilibrium detector that uses a paramagnetic material (e.g., gold doped with erbium, Au:Er) in a weak magnetic field as a temperature sensor, which can measure the temperature change produced by the absorption of X-ray photons. This temperature change leads to a change in magnetization of the paramagnetic sensor, and this response is finally measured as a flux change in a SQUID. For the LXM array, which will include ~ 100 kilo pixels, we can use the microwave multiplexing (μmux) technique for readout [3] and utilize position-sensitive detector geometry, called *hydra* [4] to reduce the number of readout channels. The *hydra* consists of multiple absorbers with different thermal couplings to the sensor. The temperature evolution in time depends upon the thermal conductance of the link between the sensor and the absorber, resulting in characteristic pulse shapes that can be discriminated.

Recently, we have fabricated a large array of MMC devices with *hydra* configuration, based on our previous work and numerical modeling of the detector response [5,6]. In this paper, we demonstrate the pulse discrimination capability of the 5×5 position-sensitive magnetic calorimeters using the pulse height and rise-time and compare the measured results to modeling results. We also report on the expected energy resolution, and the achievable energy resolution, which meets the requirement of the LXM.

2 Detector Geometries and Fabrication

The detector response is computed using the numerical calculation of the thermodynamic properties of Au:Er in a magnetic field [7], and a finite-element model to solve the temperature evolution in time for the *hydra* detector design [4]. Stevenson, et al., have explained the various approaches to maintain the high energy resolution for the large array sized MMC arrays [8]. For the LXM, the dimension of the meander-shaped pickup coil is set to 800 nm pitch, and the Au:Er (900 ppm) sensor layer is 130 nm thick. The sensor geometry is waffle-shaped for the efficient thermal coupling of *hydra* links. Inside the waffle grid is room for a stem, which supports an absorber, and a gold thermal link from the sensor to each absorber. We assume that the 25 absorbers are identical and thermally connected to the Au:Er sensor with thermal links of varying dimensions.

A single detector covers about $250 \mu\text{m}^2$ and consists of 5×5 gold absorbers thermally coupled to the Au:Er sensor. Fig. 1 shows the optical image of a fabricated Au:Er sensor and *hydra* links which are connected to the sensor with different thermal link dimensions. The meander-shaped niobium superconducting sensor coil is beneath the Au:Er sensor layer. It applies a magnetic field to the Er spins and picks up the magnetization change of the sensor. The coil, which has a pitch of $0.8 \mu\text{m}$, is fabricated by using multilayers of buried superconducting wiring and is electrically separated from the sensor with 50 nm thick SiO_2 . The effective area of the waffle-shaped Au:Er sensor is $145 \times 145 \mu\text{m}^2$. The 130 nm thick Au:Er layer is covered with 600 nm thick gold to improve the thermal diffusion time. *Hydra* links, which are 135 nm thick, connect the sensor to each absorber through the thermalization layer. Gold absorbers, which are $2.8 \mu\text{m}$ thick, not shown in Fig. 1, are fabricated by electroplating and then

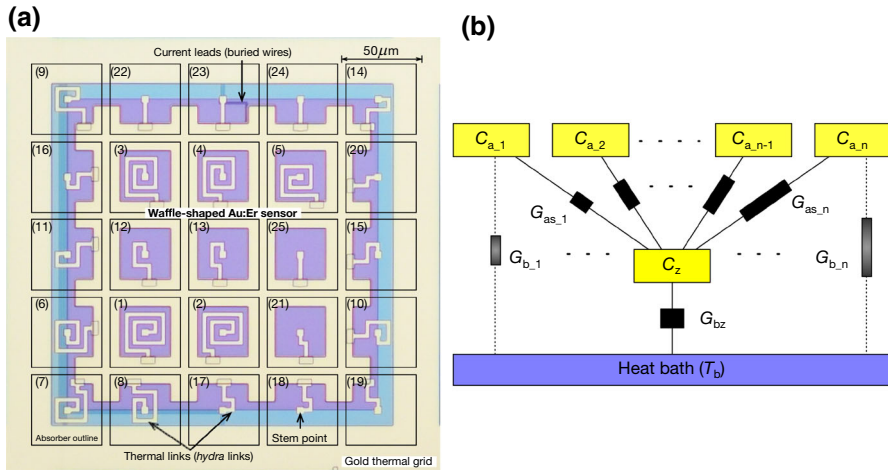


Fig. 1 (Color figure online) **a** Optical image of the fabricated waffle-shaped Au:Er sensor and *hydra* thermal links. All thermal links have the same thickness but different geometries. The rectangle shapes denote the absorbers. In terms of the arrangement of the *hydra* links, the long-low thermal coupling links are located inside of the waffle geometry, because the allowed space for each link is larger than the outer rectangle hole. The numbers in the figure denote the ascending order of the thermal conductance in this array **b** schematic diagram of the *hydra* device: C_a —heat capacity of the absorber, C_z —heat capacity of the Au:Er sensor, G_{as} —thermal conductance of the *hydra* link, G_b —thermal conductance from *hydra* link to heat bath, and G_{bz} —thermal conductance from the sensor to heat bath

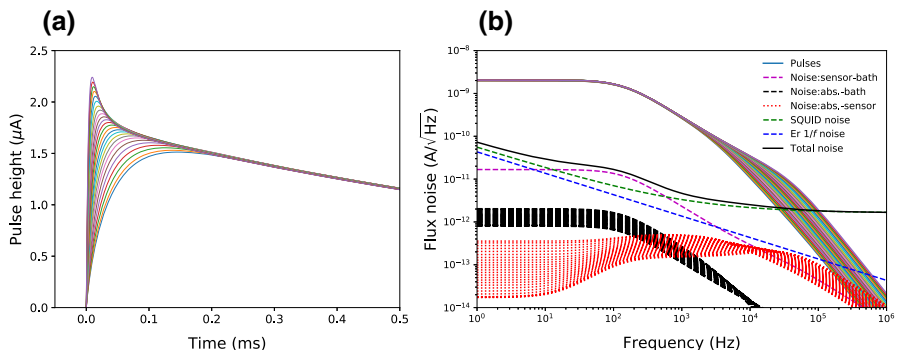


Fig. 2 (Color figure online) **a** Simulated pulse shapes for an $\text{MnK}\alpha$, 5.895 keV X-ray photon at 40 mK with parameters in Tables 1 and 2. **b** Simulated power spectral density of the pulses and each noise terms in the frequency domain

ion milled to create 5 μm gaps between them to form individual pixels. Each absorber is supported by a central 4 μm tall stem. Additional details can be found in Ref. [5].

Figure 2a shows simulated characteristic pulse shapes for the 25 pixels with parameters listed in Table 1 and 2. Figure 2b shows a plot of the simulated pulse and noise power spectral density in the frequency domain at 40 mK. The individual noise contributions are shown with dashed lines. As summarized in Tables 1 and 2, each absorber has the same heat capacity (C_a) and is coupled to the sensor through a gold thermal link, each with a different thermal conductance (G_{as}). In Table 2, G_{as} values are

Table 1 Parameters for the 25-pixel *hydra* model

Parameters	Value
Temperature (T_b)	40 mK
Erbium concentration	900 ppm
Meander coil width (pitch)	0.4 μm (0.8 μm)
Current trapped in meander coil (I_m)	15 mA
SiO ₂ insulation thickness between sensor and coil	50 nm
SQUID input sensitivity ($1/M_{is}$)	2 $\mu\text{A}/\Phi_0$
Inductance of the SQUID input coil (L_i)	13.6 nH
Inductance of the meander coil (L_m)	7.9 nH
Total stray inductance (L_{str})	5.9 nH
Heat capacity per absorber (C_a)	0.017 pJ/K
Heat capacity of the Au:Er sensor (C_z)	0.455 pJ/K
Thermal conductance from sensor to heat bath (G_{bz})	0.674 nW/K
Thermal conductance ratio from sensor to absorber (G_{as})	0.35–4.23 nW/K
Thermal conductance from <i>hydra</i> thermal link to heat bath (G_b)	10.62–1.73 pW/K

Table 2 Thermal conductance between sensor and 25-pixels (G_{as}), and thermal conductance from *hydra* links to heat bath (G_b)

Pixel	G_{as} (nW/K)	G_b (pW/K)	Pixel	G_{as} (nW/K)	G_b (pW/K)	Pixel	G_{as} (nW/K)	G_b (pW/K)
1	0.347	10.62	10	0.862	4.51	19	2.136	2.06
2	0.372	9.93	11	0.946	4.15	20	2.425	1.86
3	0.412	9.01	12	1.042	3.80	21	2.746	1.69
4	0.459	8.13	13	1.150	3.48	22	3.084	1.54
5	0.514	7.30	14	1.271	3.19	23	3.436	1.61
6	0.578	6.53	15	1.404	2.92	24	3.811	1.67
7	0.646	5.89	16	1.549	2.68	25	4.238	1.73
8	0.714	5.37	17	1.714	2.47			
9	0.785	4.92	18	1.906	2.26			

designed so as to maximize the signal-to-noise ratio and enable the discrimination of pulse shapes to determine the pixel position. The sensor and *hydra* links are deposited on a solid Si substrate, thus the thermal conductances, Au:Er sensor to heat bath (G_{bz}) and the thermal links to heat bath (G_b), are also considered.

3 Experimental Results

Fabricated devices were tested in an adiabatic demagnetization refrigerator (ADR), operating at a temperature of 50 mK. Plots illustrated in Fig. 3a show the measured pulse shapes in each of the 25 pixels at $T = 50$ mK with $I = 15$ mA trapped current

in the meander coil. The plot in the inset shows 25 clearly separated groups based on pulse height and rise-time. The pulse height is determined from the maximum value of the pulse, and the rise-time is determined from the time taken by the pulse to rise from 20 to 80%. The measured rise-times vary between $\sim 4 \mu\text{s}$ and $570 \mu\text{s}$ and the thermal decay time for overall *hydra* pixels is $\sim 1.1 \text{ ms}$.

The averaged number of events from group P1 to P24 is ~ 70 , but is ~ 200 for group P25. This is because the P25 group includes the X-ray events wherein the Au:Er sensor is hit directly. After the ion milling process, the total area of the sensor open to an X-ray photon is about 3.5 times larger than one absorber. However, only $\sim 48\%$ of 6 keV X-ray photons can be stopped in this region by the 730 nm thick Au:Er+Au thermalization layer. Therefore, the total event number of the group P25 is explained. Fig. 3b shows that the simulated pulse heights, which are in agreement with the measured data, shown in Fig. 3a, with a difference of about 10%.

The energy resolution of the *hydra* detectors is intrinsically correlated with position sensitivity. To simulate the energy resolution and position error, we used the correlated energy-position optimal filter (CEPOF) algorithm [4]. The theoretical energy resolution, ΔE , and the position resolution, Δi , are as given:

$$\Delta i = \frac{[\sum F_i S_i]^{1/2}}{2E \left[\sum F_i S_i \sum F'_i S'_i - (\sum F'_i S_i)^2 \right]^{1/2}} \quad (1)$$

$$\Delta E = \frac{[\sum F'_i S'_i]^{1/2}}{2 \left[\sum F_i S_i \sum F'_i S'_i - (\sum F'_i S_i)^2 \right]^{1/2}} \quad (2)$$

where S , S' , F , and F' are the signal responsivity, a derivative of S with respect to position of the absorber that absorbed the X-ray, optimal filter template for each absorber, and the derivative of the optimal filter with respect to the absorber position. The expected energy resolutions based on signals and noise measurements are 2.8–3.7 eV for $\text{MnK}\alpha$ at 50 mK. The simulated energy resolutions are 3.2–3.8 eV FWHM at the same measurement conditions.

The inductance of an 800 nm pitch sensor meander coil (L_m) is 7.7 nH and the estimated stray inductance (L_{str}) is 5.9 nH. For the optimization, the inductance of the SQUID input coil (L_i) needs to be the same as the sum of L_m and L_{str} . However, the L_i used in the readout circuit is only 1.8 nH; thus flux coupling is about 0.02. Upon using a SQUID with an optimized L_i of 13.6 nH, a value which is equal to the sum of L_m and L_{str} , the flux coupling can be increased by a factor of 1.6. This will result in larger pulse heights and better energy resolutions. When all parameters are optimized, the estimated energy resolutions of an 800 nm pitch sensor meander coil pixel are 2.3–2.9 eV at 50 mK. That is an improvement by almost 1 eV over the expected energy resolution based on measurement. Additionally, when the bath temperature is further decreased to 40 mK, the predicted flux change in the sensor is enhanced by a factor of 1.2. This would predict an increase in the pulse height by a factor of 1.8 over the 50 mK data, resulting in an expected energy resolution of 1.8–2.3 eV at 40 mK, as shown in Fig. 4.

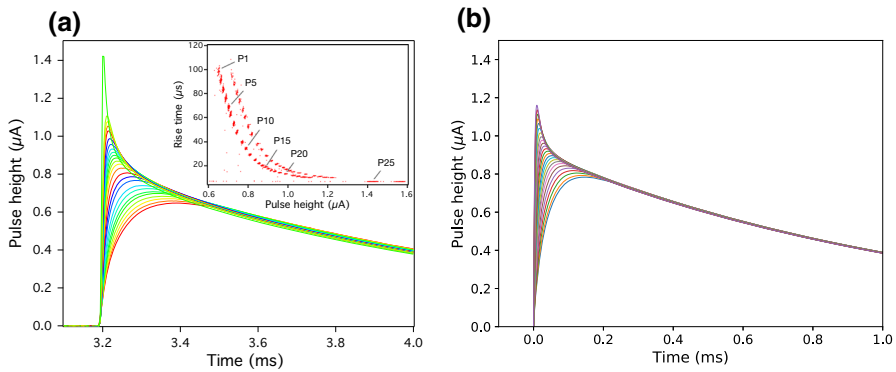


Fig. 3 (Color figure online) **a** Averaged pulse shapes for the events of the individual pixels with $I = 15$ mA trapped current at $T = 50$ mK. The inset shows 25 groups (P1–P25) clearly separated by means of rise-time (20–80%) of pulses and pulse height of measured MnK α events. The pulses decay with a similar exponential time constant of 1.1 ms. **b** Simulated pulse shapes with the same measurement conditions of **a**

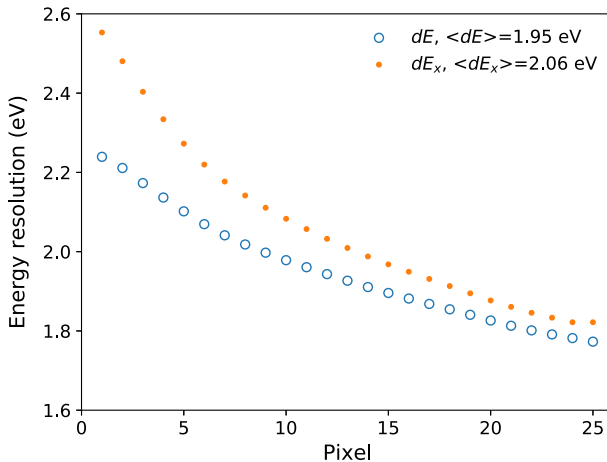


Fig. 4 (Color figure online) The estimated energy resolution of the 5×5 hydra pixels for MnK α X-ray photons at 40 mK with optimized parameters. Here, dE denotes the energy resolution without errors in position correlation, while dE_x includes the effect of the uncertainty in position determination of the X-ray absorption location for an X-ray energy of 200 eV. When the X-ray photon energy is ≥ 500 eV, the position error converges to zero and thus the energy resolution approaches dE

4 Conclusions

We have presented the first measurement results of a 25-pixel, position-sensitive hydra magnetic calorimeter. The 25 pulse shapes are clearly separated and the pulse heights agree well with the modeling. The estimated energy resolutions based on the pulse height and noise spectrum are 2.8–3.8 eV for ~ 6 keV MnK α X-ray photons at 50 mK. If the operating temperature is lowered to 40 mK and the detector is coupled to an optimized readout, the energy resolution is estimated to be 1.8–2.3 eV FWHM. Thus,

this demonstration is very promising, and we expect this *hydra* device to be capable of meeting the requirements for *Lynx*.

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