PD-9

# Improvements of our TES microcalorimeter operation system with a compact adiabatic demagnetization refrigerator cryostat

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We are developing a TES microcalorimeter operation system using a compact adiabatic demagnetization refrigerator (ADR) of our own making, keeping ground application and future missions in mind. Our ADR cryostat is composed of an FAA salt pill fabricated in-house, a superconducting magnet with a passive magnetic shield around it, and a mechanical heat switch, with a liquid helium tank as a heat sink. In LTD16, we reported the energy resolution of 3.8±0.2 eV (FWHM), when the detector was operated at 80 mK. Among the noise terms, the readout noise had the largest contribution (~3.0 eV). It turned out that the noise level of the SQUID we were using became gradually higher below 3 kHz, while the signal-to-noise ratio of the TES microcalorimeter was the highest at around a few 100 Hz. Thus, we evaluated the noise level of SQUIDs in our cryostat and adopted a gradiometer-type SQUID developed by ISAS/JAXA for TES microcalorimeter operation. When it was operated in our cryostat, the noise level was about 14 pA/√Hz in the 100-3000 Hz range. We also modified the SQUID drive circuit to remove noise source caused by the circuit. With these improvements, the energy resolution of 4.2±0.4 eV was achieved at 90 mK, which was higher than the previous measurement, and the contribution of the readout noise to the energy resolution was reduced from 3.0 eV to 1.1 eV. However, the observed noise level during operation was higher in the frequency range above 1 kHz.

## Introduction

X-ray microcalorimeter is a detector that detects photon energy temperature rise.
Energy resolution is expressed as

$$\Delta E_{\mathrm{FWHM}} = 2.35\sqrt{\frac{k_B T^2 C}{\alpha}}$$

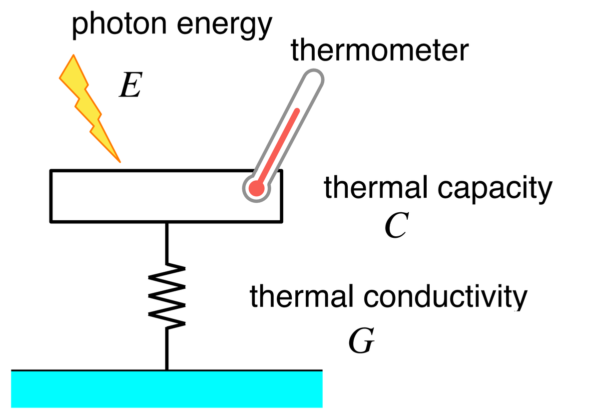


fig1. microcalorimeter schematic diagram

→ The performance of $E/\Delta E > 1000$ can be obtain at <100 mK

### *TES: Transition Edge Sensor*

- TES use sudden resistance change at superconducting transition edge as high sensitive thermometer.
- Read current change of the circuit by SQUID
- TES is kept transition edge by electro-thermal feedback

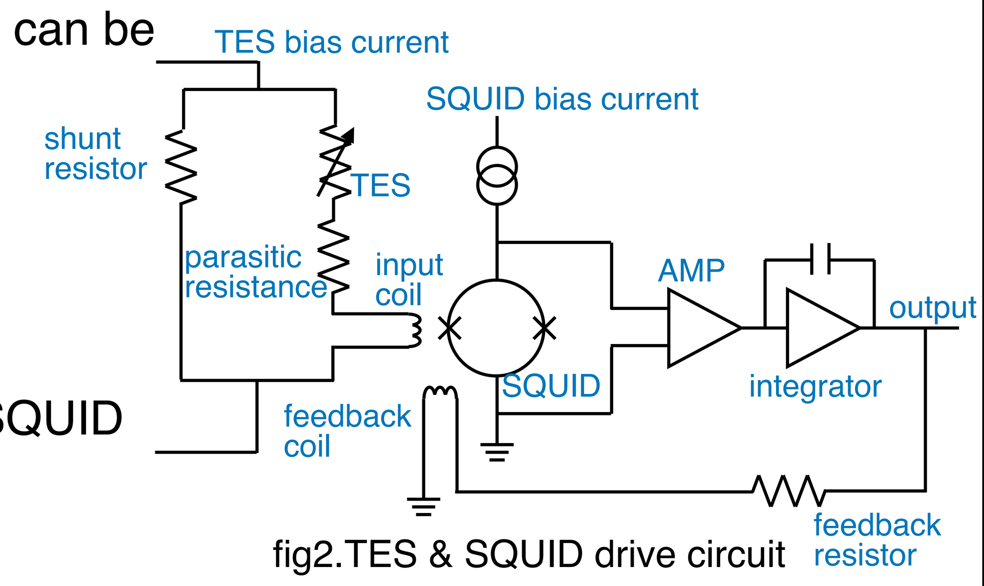


fig2.TES & SQUID drive circuit

### *ADR: Adiabatic Demagnetization Refrigerator*

ADR is suitable for making <100 mK on orbit. but it uses strong magnetic field.

↔ TES and SQUID require weak magnetic field

We develop a TES microcalorimeter together with an ADR cryostat

## ADR cryostat we developed

- FAA salt pill fabricated in-house
- Cryoperm and Nb (or Al) shield for TES and SQUID
- Temperature stability is about 10 $\mu$Krms


fig4. Appearance of cryostat

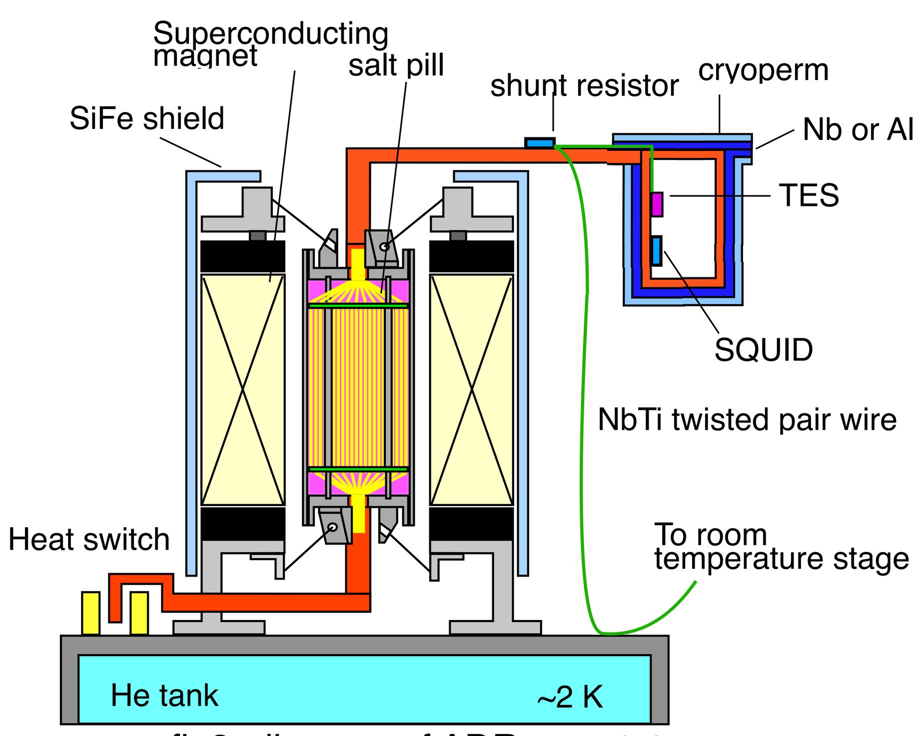


fig3. diagram of ADR cryostat

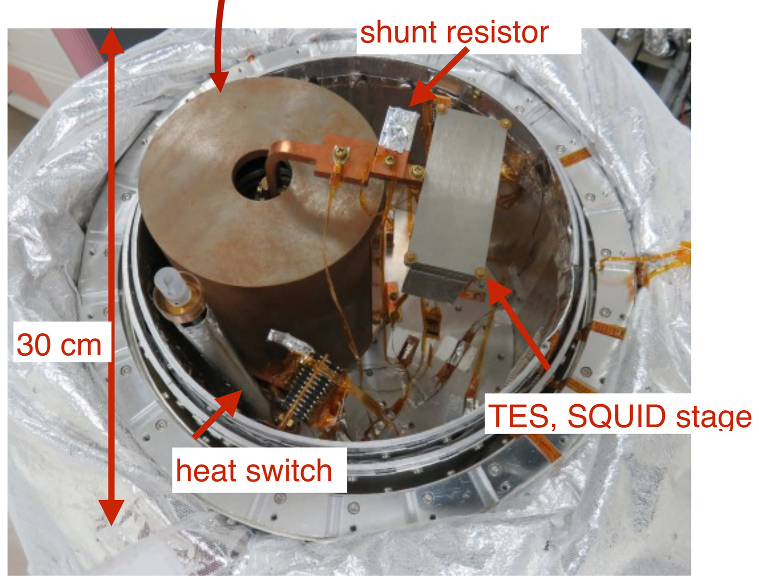


fig5. Inside ADR cryostat

## Previous results

We verified the spectroscopic performance of a TES microcalorimeter with a know energy resolution.

- TMU146-4d: ΔE = 2.8 ± 0.3 eV@6 keV (FWHM) was reported in a dilution refrigerator at Tokyo Metropolitan University (Akamatsu et al. 2009)
- In our ADR environment, we achieved 3.8 ± 0.2 eV@6 keV (Hishi et al. 2016)

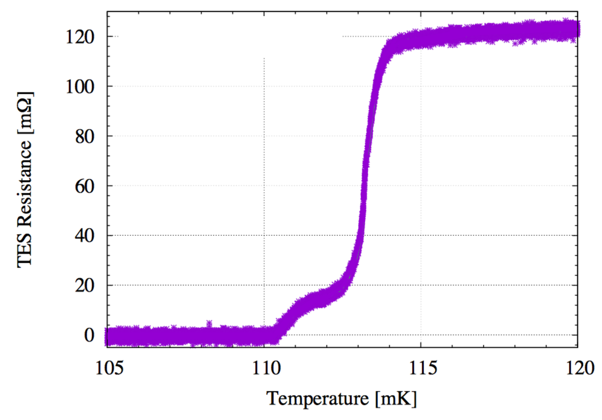


fig6. R-T curve of TMU146-4d

- Time constant of TMU146-4d ~300 $\mu$s

→ Hundreds Hz noise contribute most

- Read-out noise has 3.0 eV contribution to energy resolution.

→ We should improve read-out noise

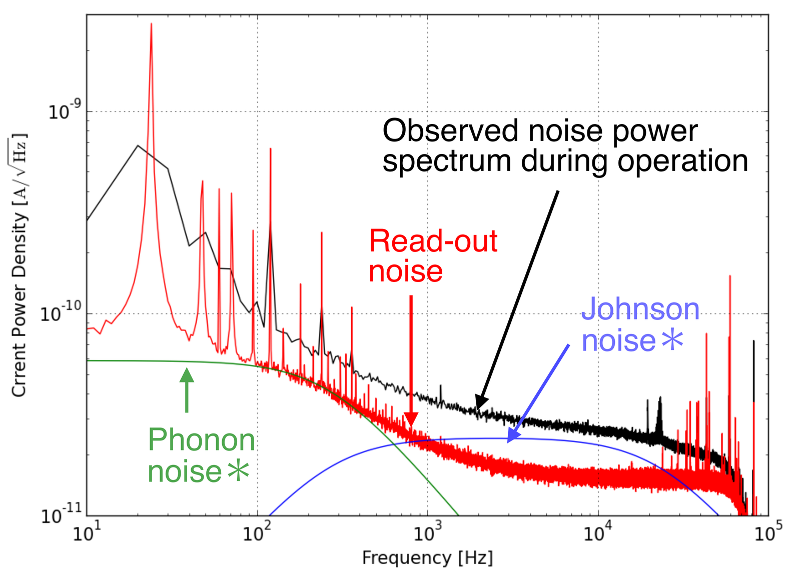


fig7. Noise power spectrum before improvement

## Improvement of read-out noise

### *change to new SQUID*

ISAS-J32: developed by ISAS/JAXA (Sakai 2014)

- gradiometer-type
  → strong for magnetic field
- low heat generation type
  → can be used on low temperature stage
- low noise at Hundreds Hz

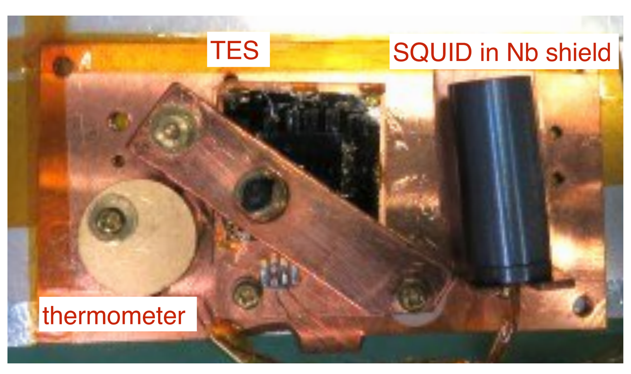


fig8. setup of low temperature stage

### *improvement of SQUID drive circuit*

**Current limiting resistor**

In the original circuit, 50 Ω resistors were used to limit current to the first amplifier.

→ In our application, wires between the cold stage and the room temperature have comparable resistance. Hence, we removed these resistors, to suppress Johnson noise.

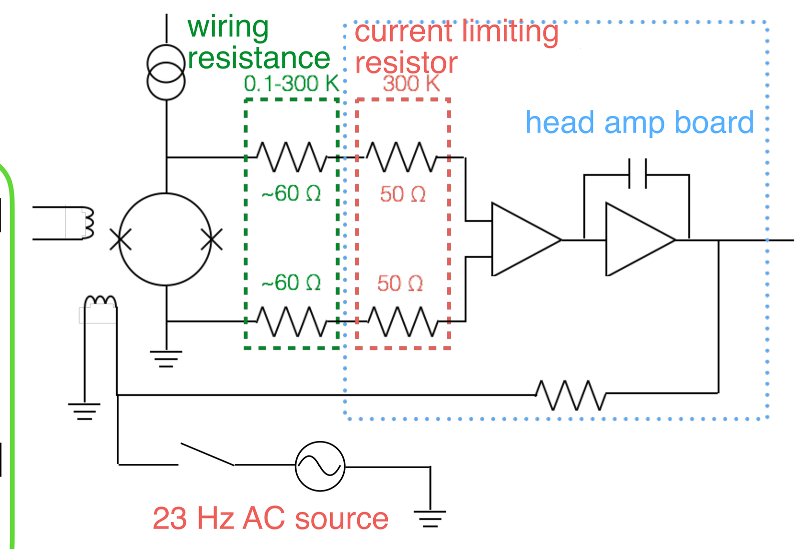


fig9.noise source of SQUID drive circuit

**23 Hz AC source**

In the original circuit, a 23 Hz AC source was used to adjust the SQUID operating point. This caused strong noise of 23 Hz and its harmonics.

→ We modified the circuit design to use an external function generator for adjusting the SQUID operating point, and completely removed this noise source.

### *improvement results*

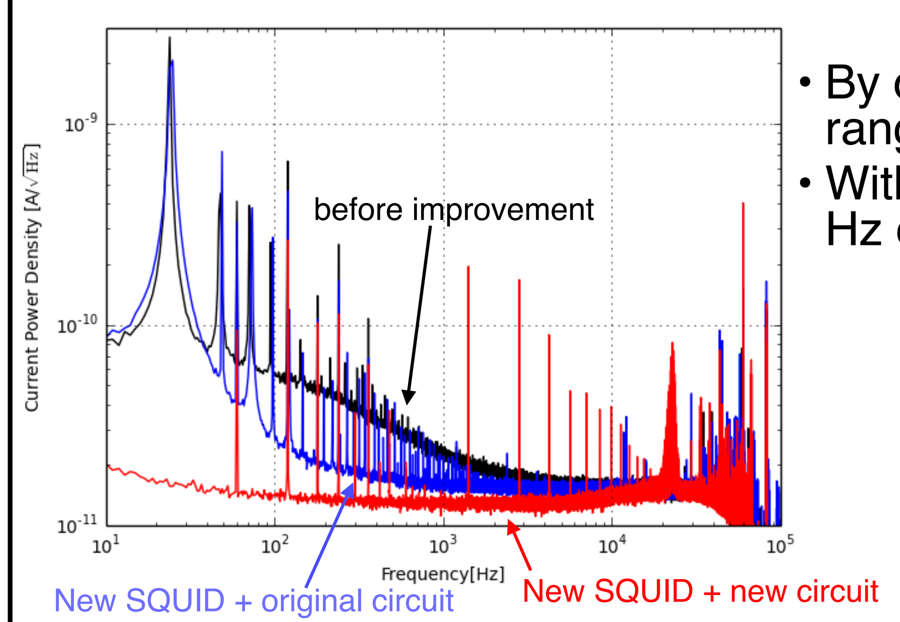


fig10. Power spectrum of read-out noise

- By changing SQUID noise level in the $10^2$-$10^3$ Hz range was reduced to ~14 pA/√Hz.
- With improvement of SQUID drive circuit, the 23 Hz compornent and its harmonics were excluded.

Using the new SQUID and improved drive circuit, the same TES microcalorimeter was operated. Due to cooling problem, the detector was operated at 90 mK.

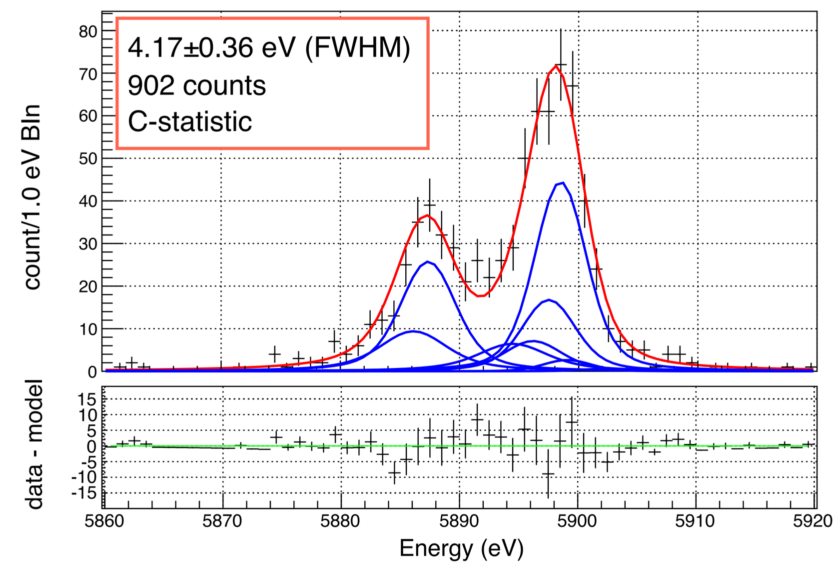


fig11. Energy spectrum

→ 4.17±0.36 eV (FWHM)

→Similar ΔE compared with Hishi et al. (2016), in spite of the higher bath temperature. However, improvement of the energy resolution was not explicitly demonstrated.

## Noise components

baseline noise 3.2 eV→3.9 eV
- read-out noise 3.0 eV→1.1 eV
- TES intrinsic noise 1.5 eV→3.7 eV
  - phonon noise∗ 0.8 eV→2.4 eV
  - johnson noise∗ 1.2 eV→2.8 eV

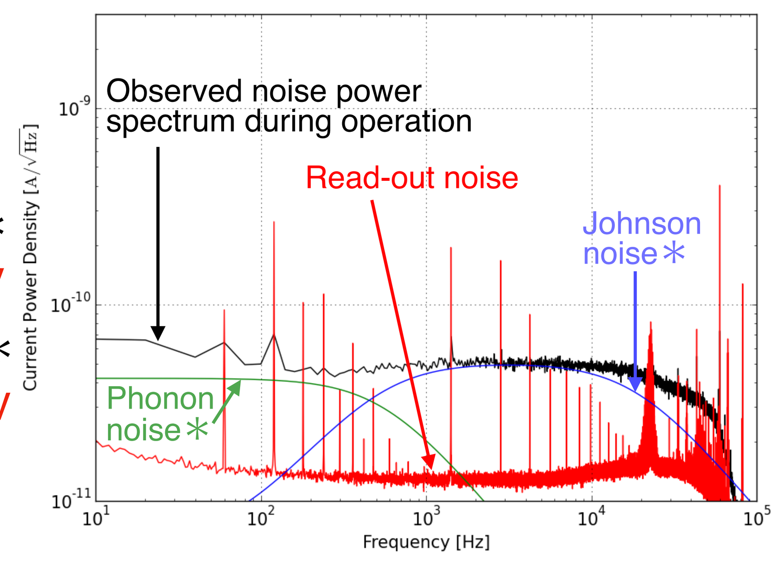


fig12. Noise power spectrum after improved read-out
∗: excess components were included

Though the readout noise has decreased, the noise above ~1 kHz increased during operation. A further analysis is needed to understand the reason.

tab1. Comparison of TES driving parameters

| | before | after |
|---|---|---|
| TES current [uA] | 10.6 | 14.5 |
| TES resistance [mΩ] | 25.9 | 16.9 |
| shunt resistance [mΩ] | 2.11 | 1.41 |
| parasitic resistance [mΩ] | 0.95 | 1.63 |
| TES temperature [mK] | 112.57 | 117.8 |
| Heat bath temperature [mK] | 80 | 90 |

In the present configuration, there exists a relatively large parasitic resistance near the TES or the SQUID. Its impact needs to be investigated.

## Conclusion

- We investigated the noise characteristics of the SQUID and its readout circuit used in our TES microcalorimeter system.
- By changing the SQUID and optimizing its drive circuit, the readout noise was significantly improved. Its contribution to the energy resolution was reduced from 3.0 eV to 1.1 eV.
- A similar energy resolution was achieved at 90 mK, which was higher than the previous measurement.
- However, the observed noise above ~1 kHz increased during operation. A further analysis is needed to understand the reason and improve the performance.

### *Reference*


- Akamatsu et al., AIP Conf. Proc. 1185, 195 (2009)
- Hishi et al., J Low Temp Phys 184, 583-589 (2016)
- Sakai, PhD. Thesis, University of Tokyo (2014)