Demonstration of MHz frequency domain multiplexing readout of 37 transition edge sensors for high-resolution X-ray imaging spectrometers

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We report on the development and demonstration of a MHz frequency domain multiplexing (FDM) technology to read out arrays of cryogenic transition edge sensor (TES) X-ray microcalorimeters. In our FDM scheme, TESs are AC biased at different resonant frequencies in the low MHz range through an array of high-Q LC resonators. The current signals of all TESs are summed at superconducting quantum interference devices (SQUIDs). We have demonstrated multiplexing for a readout of 31 pixels using room temperature electronics, high-Q LC filters and TES arrays developed at SRON, and SQUID arrays from VTT. We repeated this on a second setup with 37 pixels. The summed X-ray spectral resolutions @ 5.9 keV are $\Delta E_{31\text{pix} \text{MUX}} = 2.14 \pm 0.03$ eV and $\Delta E_{37\text{pix} \text{MUX}} = 2.23 \pm 0.03$ eV. The demonstrated results are comparable with other multiplexing approaches. There is potential to further improve the spectral resolution and to increase the number of multiplexed TESs, and to open up applications for TES X-ray microcalorimeters.

High-resolution X-ray spectroscopy is one of the most powerful techniques to understand the chemical composition of materials and the ionization state of plasma. It can be applied to a wide range of scientific fields varying from materials science to the physics of hot plasma in the Universe. Applied to a wide range of scientific fields varying from materials and the ionization state of plasma. It can be applied to a wide range of scientific fields varying from materials and the ionization state of plasma.

We are developing FDM readout technology for astronomy in space, such as the X-ray Integral Field Unit (X-IFU) instrument on board the European X-ray astronomical satellite Athena, and for future astronomical project. For the Athena X-IFU instrument, 34 pixels within a frequency band of 1–5 MHz and spectral resolution $\Delta E = 2.5$ eV @ 7 keV are required. In this letter, we report the recent progress for FDM readout of 37 pixels of TES X-ray microcalorimeters.

For the FDM readout demonstration reported here, we used two setups, called XFD (Figure A) and 40-pixel. The names come simply from the development work at the time and we concentrate here only the details of the XFD setup. Figure B shows the schematic diagram of the cryo-electronics. The

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$Q = \frac{1}{2 \pi R C}$

$E = \frac{Q}{2}$

$\Delta E = \frac{Q}{2 \pi f}$

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$\Delta E_{31\text{pix} \text{MUX}} = 2.14 \pm 0.03$ eV and $\Delta E_{37\text{pix} \text{MUX}} = 2.23 \pm 0.03$ eV.
lithographically-made high-\( Q \) LC filters contain parallel plate Nb/SiN\(_{x}\)/Nb capacitors and Nb-based gradiometric spiral coil. \[1\] The inductor value is fixed, and the resonance frequencies are defined by the capacitor values. In this report, we used 32 LC resonator chips with 2 µH coils (40 resonators for the 40-pixel setup) and resonances between 1 and 5 MHz with 100 kHz separation (Fig.2A). A shunt resistance \( R_{\text{shunt}} \) (0.75 Ω) is implemented at the 50 mK stage. As shown in Fig.2 middle, the LC filter contains a capacitive bias voltage divider with a ratio of 1:25, which makes an effective shunt resistance at the TES side to be 1.1 mΩ. The measured \( Q \)-factor when the TES is in the superconducting state is around \( Q \approx 16000 \times (f/[\text{MHz}]) \), limited by the effective shunt resistance in the circuit. To be able to optimize the bandwidth of different TES designs, a superconducting transformer per pixel is employed. In this work, a transforming turns ratio of \( n = 1 : 1.125 \) with a coupling factor \( k = 0.94 \) is used. Under this configuration, TES are loaded by the effective inductance of 3.6 µH.

The SQUIDs-based amplifier is the most important component to read out a large number of TESs. We are using two-stage SQUID amplifiers, developed at VTT and which consist of 6 loops first stage and 184 \( \times \) 4 loops 2nd stage SQUIDs. Together with a SRON-developed low noise amplifier (LNA), the typical readout current noise, referred to the SQUID input, is \( \sim 5 \text{ pA}/\sqrt{\text{Hz}} \), which is much lower than the typical TES noise (~30-50 pA/\( \sqrt{\text{Hz}} \)). To avoid any undesired behaviour of the SQUIDs due to the coupling between the input coil of the SQUIDs, and parasitic inductance and capacitance in the LC filter, an RC filter with components \( R = 1 \Omega \) and \( C = 5 \text{ pF} \) is implemented just before the input coil of the first stage SQUID.

In our system, the multiplexed data is acquired with 20 M samples/s and the de-multiplexed data streams are decimated down to 156 k samples/s by using 4 stage filters on an SRON “DEMUX” digital board. The DEMUX board, using AD9726 DACs and a Xilinx XC7V585T Virtex 7 FPGA, generates a modulated comb of AC bias frequencies for the TESs and the signals for the base-band feedback loop. To increase the linearity and dynamic range of the SQUIDs, the phase delay due to the harness between the room temperature electronics and cold electronics is compensated by the baseband feedback.\[12\]

The TES signals are demodulated and re-modulated with a controlled phase shift by the FPGA on the DEMUX board before being fed back to the system. The details of our digital system can be found in den Hartog et al. 2012 and 2014.\[13\]

For the FDM demonstration reported here, we employed detector arrays fabricated at SRON.\[18\] They consist of a high-aspect ratio TES bilayer \( 80 \times 13 \mu\text{m} \) of Ti (35 nm) and Au (200 nm), located on a 0.5 µm thick Si\(_{3}N_{x}\) membrane and coupled to a 240\( \times \)240 µm Au absorber. The elongated shape towards the direction of current flow was employed to suppress the frequency dependent non-linearity\[19\] by increasing TES resistance. The thickness of the absorber is 2.35 µm to ensure high quantum efficiency (83% at 6 keV). The critical temperature \( T_c \) of the bilayer is tuned to be around 83 mK and the thermal conductance at \( T \) is \( G \approx 0.85 \text{ pJ/K} \). To reduce frequency dependent detector behaviour under AC bias, we use high aspect ratio TESs. This device was extensively investigated under AC bias with a lower inductance \( L_{\text{eff}} = 1 \mu\text{H} \) and demonstrated an excellent spectral resolution of 1.8 eV FWHM.\[20\]

To characterise the performance of the TES, we used a \(^{55}\text{Fe} \) source located on the cryogenic platform. The count rate was typically 1 count/s/pixel. Each pulse was processed by the optimal filtering process\[21\] in the frequency space by using the time average pulse weighted by noise spectra. Long-term gain drift correction was performed based on TES baseline current and pulse height information. The energy non-linearity was corrected by using the zero energy (0 keV), Mn-K\( \alpha \) (5.9 keV) and Mn-K\( \beta \) (6.5 keV) information. The resultant energy spectrum was fitted with the Mn-K\( \alpha \) line model\[22\] convolved with the detector resolution. To avoid fitting bias, we employed Cash statistics.\[23\]

Previous demonstrations with FDM readout of TES spectrometers was mainly limited by three effect.\[24\] These are 1.)
degradation of energy resolution due to carrier leakage from neighbouring resonators. 2.) the degradation due to inter-modulation distortion from the DACs, and 3.) frequency dependent non-linearity due to the Josephson junction in TESs under MHz AC bias. We solved or mitigated these effects using the following approaches.

Carrier leakage from neighbouring pixels degrades the performance. The origin of this issue is that when the electrical bandwidth \((R/L)\) of the devices is too large with respect to the frequency spacing, TESs become sensitive to the AC bias voltage of neighbouring frequencies. Therefore it is different from the electrical cross-talk due to parasitic and common inductance and capacitance. In the carrier leakage case, the TES voltage is modulated by \(f_{\text{target}} - f_{\text{nei}}\), where \(f_{\text{target}}\) is a bias frequency of the target pixel and \(f_{\text{nei}}\) are the neighbouring frequencies. Although it could be avoided by applying large frequency separation or applying a phase window, these approaches would not be a practical solution in a real instrument. Instead, we solved the issue of excessive electrical bandwidth by increasing the inductance of the LC filter. However, too large an inductance will lead to an instability due to the electrical-thermal feedback at the critical inductance. Moreover, large \(L\) can lead to worse performance due to non-linear effects such as a large excursion in the resistance-temperature space (e.g., Fig. 4 of Kilbourne et al. 2008). The critical inductance can be estimated using the equation (7) in Smith et al. 2016 showing strong dependency on the detector thermal time constant \((\sim C/G)\), sensitivity to temperature \((\alpha)\) and current \((\beta)\) dependency. Previously these optimizations were hampered due to different \(\alpha\), \(\beta\) and the rather high \(G\) of the available devices. In this report, we used a factor 5 narrower electrical bandwidth configuration compared to the previous work. The improvement is realized by the combination of a slower detector time constant and a different \(\alpha - \beta\) relationship. Typical detector time constants are rise time \(\tau_{\text{rise}} \sim 180\) µs and fall time \(\tau_{\text{fall}} \sim 1.1\) ms.

Inter-modulation products from non-linearity in the system are an issue for the detector performance and system dynamic range. In this report we refer to such products as inter-modulation line noise (IMLN). Since more than 30 carriers are generated by the DAC, IMLN will be an additional noise term when it falls into the detector thermal response band (< 1kHz). This IMLN will degrade the performance and limit the number of multiplexed pixels. This issue can be avoided by using carriers in a frequency arrangement where the frequency spacing between all subsequent carriers are on a regular grid (called grid-frequency). However, this will be a trade-off with the performance degradation due to an additional (virtual) shunt resistance resulting from operating off-resonance \((2 \times 2\pi L \Delta f)\). Furthermore, LC filter fabrication accuracy puts a limit on the attainable resonance frequency distribution. To overcome the problem, we developed a frequency shift algorithm, which allows us to shift a resonator digitally without losing the performance. The basic concept and practical demonstration are given in previous works. The multi-pixel behaviour was characterized carefully and we concluded that we could operate the system with more than 40 pixels, without the current DAC going into saturation. In this report we used the grid frequency 1.0-2.0 kHz, which is well above the thermal bandwidth.

A frequency dependent non-linear behaviour under MHz AC bias was observed in previous demonstrations. The issue results from the so-called proximity effect where the local order parameter of the bilayer is modified by the connection to the niobium leads. The resulting structure shows similar behaviour to a weak superconducting link. Under MHz AC bias, this effect shows several characteristics such as non-linear response, a Fraunhofer-like dependence of the
TABLE I. Summary of the FDM demonstrations

| Setup    | N.res | N.MUX | $\Delta E_{\text{Single}}$ | $\Delta E_{\text{MUX}}$ | $\Delta E_{\text{deg}}$ |
|----------|-------|-------|-----------------------------|--------------------------|--------------------------|
| XFDM     | 32    | 31    | 1.95                        | 2.14±0.03                | 0.9                      |
| 40-pixel | 38    | 37    | 2.05                        | 2.23±0.03                | 1.0                      |

$\Delta E_{\text{deg}} = \Delta E_{\text{MUX}}^2 - \Delta E_{\text{single}}^2$

In the XFDM setup, 1 resonator is affected by multiple IMLN.
In the 40-pixel setup, 1 resonator is affected by multiple IMLN and 2 resonators are missing due to fabrication yield.

Critical current on magnetic field and steps in the superconducting transition. The resulting negative effect on the energy resolution scales with the resistance of the TES and is higher for low-ohmic TESs. By comparing devices with different impedance and saturation power, the power needed to drive TES into the normal state, we confirmed our prediction[19] that the Josephson current decreases with the increase of the superconducting phase difference over the TES, $\Phi \sim \frac{P}{R}$, where $P$ is the detector power, $R$ is the resistance, and $\omega$ is the bias frequency. Accordingly, high-power and high-resistance devices show the least degradation of the energy resolution. Since the detector power is defined by the application, we modified the detector resistance by changing the aspect ratio of the TESs. Despite the large normal resistance $R_N$, we have shown that the internal thermal fluctuation noise remains small for these devices.[12] Moreover, a high aspect ratio TES minimizes the impact of the loss due to eddy currents. The average single pixel performance over 1–5 MHz $\langle \Delta E_{\text{Single}} \rangle$ is given in Table I and is slightly worse than one with small inductance measurements ($\Delta E_{\text{small}} L \sim 1.8$ eV). This is likely due to the large inductance, and the non-linearity and large signal effects associated with that. For the demonstration setups, a 8×8 TES array is implemented for the XFDM and a 32×32 TES array for the 40-pixel.

After the implementation of all mitigating measures discussed above, we performed a demonstration of the FDM readout. The TESs were operated around 20% of the transition. The AC-bias was set to about 50% of the maximum level, and the signal feedback to about 36%. The crest factors were about 7 in both signals. The electrical cross-talk events were decreased, and the signal feedback to about 36%. The electrical cross-talk events were decreased, and the signal feedback to about 36%. The electrical cross-talk events were decreased, and the signal feedback to about 36%. The electrical cross-talk events were decreased, and the signal feedback to about 36%.

Testing these devices and optimizations in multiplexed mode requires different cryogenic components that are not yet available (e.g., LC filters and transformers). Considering the well-described scaling relation shown in Fig 3 and the fact that the bottlenecks are identified, we see room for improvement in a future demonstration together with a better single-pixel performance device.

In summary: we have shown a demonstration of FDM multiplexed readout of 31 pixels from an 8×8 TES array and 37 pixels from a 32×32 TES array, both fabricated at SRON. Our current best results are $\Delta E_{\text{MUX31pixels}} = 2.14 \pm 0.03$ eV, $\Delta E_{\text{MUX37pixels}} = 2.23 \pm 0.03$ eV at 5.9 keV. The performance of these demonstrations is comparable to those reported by other multiplexing technologies (Fig 5). This FDM readout technology will provide a means to increase the number of pixels in TES X-ray spectrometers for various fields from ground-based science to astronomy (X-ray spectroscopy) and from infrared to cosmic microwave background measurements[3].
Data availability

The data that support the findings of this study are available from the corresponding or contributing authors upon reasonable request.

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1C. Enss, Cryogenic Particle Detection Vol. 99 (2005).
2M. Kiviranta, H. Seppä, J. van der Kooi, and P. de Korte, “SQUID-based readout schemes for microcalorimeter arrays,” in Low Temperature Detectors (American Institute of Physics Conference Series, Vol. 605, edited by F. S. Porter, D. McCammon, M. Galeazzi, and C. K. Stahle) (2002) pp. 295–300.
3M. Durkin, J. S. Adams, S. R. Bandler, J. A. Chervenak, S. Chaudhuri, C. S. Dawson, E. V. Denison, W. B. Doriese, S. M. Duff, F. M. Finkbeiner, C. T. FitzGerald, J. W. Fowler, J. D. Gard, G. C. Hilton, K. D. Irwin, Y. I. Joe, R. L. Kelley, C. A. Kilbourne, A. R. Miniussi, K. M. Morgan, G. C. O’Neil, C. G. Pappas, F. S. Porter, D. McCammon, K. Sakai, S. J. Smith, R. W. Stevens, D. S. Swetz, P. Szpyrski, J. N. Ullom, L. R. Vale, N. A. Wakeham, J. C. Weber, and B. A. Young, “Demonstration of Athena X-Future Compatible 40-GHz Time-Division-Multiplexed Readout,” IEEE Transactions on Applied Superconductivity 29, 2904472 (2019).
4K. M. Morgan, B. K. Alpert, D. A. Bennett, E. V. Denison, W. B. Doriese, J. W. Fowler, J. D. Gard, G. C. Hilton, K. D. Irwin, Y. I. Joe, G. C. O’Neil, C. D. Reintsema, D. A. Rudman, K. Sakai, S. J. Smith, R. W. Stevens, D. S. Swetz, P. Szpyrski, J. N. Ullom, L. R. Vale, N. A. Wakeham, J. C. Weber, and B. A. Young, “Demonstration of Athena X-Future Compatible 40-GHz Time-Division-Multiplexed Readout,” IEEE Transactions on Applied Superconductivity 29, 2904472 (2019).
5K. M. Morgan, B. K. Alpert, D. A. Bennett, E. V. Denison, W. B. Doriese, J. W. Fowler, J. D. Gard, G. C. Hilton, K. D. Irwin, Y. I. Joe, G. C. O’Neil, C. D. Reintsema, D. A. Rudman, K. Sakai, S. J. Smith, R. W. Stevens, D. S. Swetz, P. Szpyrski, J. N. Ullom, L. R. Vale, N. A. Wakeham, J. C. Weber, and B. A. Young, “Demonstration of Athena X-Future Compatible 40-GHz Time-Division-Multiplexed Readout,” IEEE Transactions on Applied Superconductivity 29, 2904472 (2019).
6J. van der Kooi, L. G. Gottardi, H. Akamatsu, B. J. van Leeuwen, R. den Hartog, D. Haas, M. Kiviranta, and B. J. Jackson, “Optimising the multiplex factor of the frequency domain multiplexed readout of the TES-based microcalorimeter imaging array for the X-IFU instrument on the Athena x-ray observatory,” in Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray (2017) pp. 99055R, edited by J.-W. A. den Herder, L. Piro, M. Cappi, J. Houvelin, D. Barret, T. Lam Trong, J.-W. den Herder, L. Piro, M. Cappi, J. Houvelin, D. Barret, T. Lam Trong, J.-W. den Herder, L. Piro, M. Cappi, J. Houvelin, D. Barret, T. Lam Trong, J.-W. den Herder, L. Piro, M. Cappi, J. Houvelin, D. Barret, T. Lam Trong, J.-W. den Herder, L. Piro, M. Cappi, J. Houvelin, D. Barret, T. Lam Trong, J.-W. den Herder, L. Piro, M. Cappi, J. Houvelin, D. Barret, T. Lam Trong, J.-W. den Herder, L. Piro, M. Cappi, J. Houvelin, D. Barret, T. Lam Trong, J.-W. den Herder, L. Piro, M. Cappi, J. Houvelin, D. Barret, T. Lam Trong, J.-W. den Herder, L. Piro, M. Cappi, J. Houvelin, D. Barret, T. Lam Trong, J.-W.
"Super DIOS mission for exploring “dark baryon”", in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 11444 (2020) p. 1144450.

M. P. Bruijn, A. J. van der Linden, L. Ferrari, L. Gottardi, J. van der Kuur, R. H. den Hartog, H. Akamatsu, and B. D. Jackson, "LC Filters for FDM Readout of the X-IFU TES Calorimeter Instrument on Athena," Journal of Low Temperature Physics 193, 661–667 (2018).

M. V. Kiviranta, L. Grönborg, and J. van der Kuur, “Two SQUID amplifiers intended to alleviate the summing node inductance problem in multiplexed arrays of Transition Edge Sensors," arXiv e-prints , arXiv:1810.09122 (2018), arXiv:1810.09122 [astro-ph.IM].

M. V. Kiviranta, L. Grönborg, T. Puranen, J. van der Kuur, N. Beev, J. Salonen, D. Hazza, and S. Korpela, “Two-Stage SQUID Amplifier for the Frequency Multiplexed Readout of the X-IFU X-Ray Camera," IEEE Transactions on Applied Superconductivity 31, 3060556 (2021).

Q. Wang, M. D. Audley, P. Khotropanah, J. van der Kuur, G. de Lange, A. Aminiai, D. Boersma, F. van der Tak, and J.-R. Gao, “Noise Measurements of a Low-Noise Amplifier in the FDM Readout System for SAFARI," Journal of Low Temperature Physics 199, 817–823 (2020).

L. Gottiard, M. Kiviranta, J. van der Kuur, H. Akamatsu, M. P. Bruijn, and R. den Hartog, “Nearly Quantum Limited Two-Stage SQUID Amplifiers for the Frequency Domain Multiplexing of TES Based X-ray and Infrared Detectors," IEEE Transactions on Applied Superconductivity 25, 2369234 (2015).

R. den Hartog, D. Boersma, M. Bruijn, B. Dirks, L. Gottiard, H. Hoevers, R. Hou, M. Kiviranta, P. de Korte, J. van der Kuur, B. J. van Leeuwen, A. Nieuwenhuizen, and M. Popescu, “Baseband Feedback for Frequency-Domain-Multiplexed Readout of TES X-ray Detectors," in American Institute of Physics Conference Series, Vol. 1185, edited by B. Young, B. Cabrera, and A. Miller (2009) pp. 261–264.

R. den Hartog, B. J. van Leeuwen, P. Peille, J. van der Kuur, L. Ravera, D. van Loon, B. Jackson, and J. W. den Herder, “Performance of a state-of-the-art DAC system for FDM readout," in Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 10699, edited by J.-W. A. den Herder, W. Cash, “Parameter estimation in astronomy through application of the Marquardt algorithm," Research in Astronomy & Astrophysics 2, 551–554 (2002).

K. Nagayoshi, M. L. Rider, M. P. Bruijn, L. Gottardi, E. Taralli, P. Khotropanah, H. Akamatsu, S. Visser, and J. R. Gao, “Development of a TES Microcalorimeter Array as a Backup Sensor for the Athena/X-IFU Instrument," Journal of Low Temperature Physics 199, 943–948 (2020).

U. Gottiard, S. J. Smith, A. Kozorezov, H. Akamatsu, J. van der Kuur, S. R. Randler, M. P. Bruijn, J. A. Chervenak, J. R. Gao, R. H. den Hartog, B. D. Jackson, P. Khotropanah, A. Miniusi, K. Nagayoshi, M. Rider, J. Sadleir, K. Sakai, and N. Wakeham, “Josephson Effects in Frequency-Domain Multiplexed TES Microcalorimeters and Bolometers," Journal of Low Temperature Physics 193, 209–216 (2018).

M. de Wit, L. Gottiard, E. Taralli, K. Nagayoshi, M. L. Rider, H. Akamatsu, M. P. Bruijn, M. D’Andrea, J. van der Kuur, K. Ravensberg, D. Vaccaro, S. Visser, J. R. Gao, and J. W. den Herder, “High aspect ratio transition edge sensors for x-ray spectrometry," Journal of Applied Physics 128, 224501 (2020).

A. E. Szymkowiak, R. L. Kelley, S. H. Moseley, and C. K. Stahle, “Signal processing for microcalorimeters," Journal of Low Temperature Physics 93, 281–285 (1993).

G. Hölzer, M. Frisch, M. Deutsch, J. Härtwig, and E. Förster, “Kέτζα2 and Kέτζα3 x-ray emission lines of the 3d transition metals," Phys. Rev. A 56, 4554–4568 (1997).

W. Cash, “Parameter estimation in astronomy through application of the likelihood ratio," Astrophys. J. 228, 939–947 (1979).

J. S. Kastra and J. A. M. Bleeker, “Optimal binning of X-ray spectra and response matrix design," Astronomy & Astrophysics 587, A151 (2016) arXiv:1601.05309 [astro-ph.IM].

H. Akamatsu, L. Gottiard, J. van der Kuur, C. P. de Vries, M. P. Bruijn, J. A. Chervenak, M. Kiviranta, A. J. van den Linden, B. D. Jackson, A. Miniusi, K. Ravensberg, K. Sakai, S. J. Smith, and N. Wakeham, “Progress in the Development of Frequency-Domain Multiplexing for the X-ray Integral Field Unit on Board the Athena Mission," Journal of Low Temperature Physics 199, 737–744 (2020) arXiv:2003.11899 [astro-ph.IM].
J. E. Sadleir, S. J. Smith, I. K. Robinson, F. M. Finkbeiner, J. A. Chervenak, S. R. Bandler, M. E. Eckart, and C. A. Kilbourne, “Proximity effects and nonequilibrium superconductivity in transition-edge sensors,” Phys. Rev. B 84, 184502 (2011), arXiv:1108.4632 [cond-mat.supr-con].

L. Gottardi and K. Nagayashi, “A review of x-ray microcalorimeters based on superconducting transition edge sensors for astrophysics and particle physics,” Applied Sciences 11 (2021), 10.3390/app11093793.