Time-division and code-division SQUID multiplexers for TES microcalorimeter arrays: the analog readout chain

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NIST's SQUID time-division multiplexer (TDM) is a highly successful readout architecture that has been deployed worldwide in many recent 250-pixel-scale TES microcalorimeter spectrometers. Fielded systems include a gamma-ray spectrometer for analysis of special nuclear materials (Los Alamos) and X-ray spectrometers for particle-induced emission (Jyvaskyla), time-resolved absorption spectroscopy (Lund University; NIST), synchrotron-based soft-X-ray absorption and emission spectroscopy (Brookhaven), synchrotron-based energy-resolved scattering (Argonne), and fluorescence spectroscopy of pionic atoms (Paul Scherrer Institute).

In our TDM readout architecture, each dc-biased TES has its own first-stage SQUID. Rows of first-stage-SQUIDs are turned on and off sequentially such that the signal from only one TES at a time per readout column is passed to a series-array SQUID, to a room-temperature preamplifier, and to digital-feedback electronics. The present specifications of fielded TDM systems include a row period of 320 ns and non-multiplexed amplifier noise of 0.4 u-phi_0/sqrt(Hz) (referred to the first-stage SQUID). This performance has been good enough to allow high-resolution X-ray spectra to be acquired with 2.7 eV average energy resolution (full-width-at-half-max, or FWHM) at the benchmark Mn Ka line (5.9 keV) in 8-row TDM. Eight-column by 30-row (240 pixel) arrays are now routinely fielded for science and achieve 3.5 to 4.5 eV energy resolution at 5.9 keV and approaching 1.0 eV resolution at 500 eV.

Our SQUID code-division multiplexer (CDM) operates similarly to our TDM one (TESs are dc-biased and first-stage SQUIDs are switched on one at a time). The main difference is that while TES signals are switched on and off in TDM, in CDM the polarity of the TES signals is switched. The advantage is that all TESs are observed by the multiplexer at all times, which removes the sqrt(N_rows) noise-aliasing degradation that is inherent in TDM. We are developing flux-summing CDM to be drop-in compatible with our TDM systems. Our CDM system has achieved 2.6 eV average energy resolution (FWHM) at 5.9 keV in an 8-row demonstration.

To enable future TES microcalorimeter arrays, which are being planned to have more pixels (kilopixel-scale or larger), faster detectors (decay-time constants decreasing below 250 μs) for higher pix-pixel count rates, or both, we are improving our TDM and CDM readout systems. Near-term goals are 160 ns row times and non-multiplexed amplifier noise as good as 0.2 u-phi_0/sqrt(Hz). We are also working to decrease the present part-per-thousand-level inductive crosstalk among readout elements within a column.

Here we present our recent and continuing progress in TDM and CDM development. Upgrades to be discussed include new SQUID-multiplexer chips (both TDM and CDM), new series-array SQUID amplifiers, and a new room-temperature preamplifier circuit. Further, we detail our mitigation of bandwidth limitations brought about by the interactions among the various system components and the cryogenic wiring that interconnects them. With these improvements, the TDM system can now achieve row-switching times of 200 ns, and 160 ns row switching is within view. Finally, we present our latest results in reading out TES microcalorimeter arrays with both TDM and CDM circuits of up to 32 rows per column. New results include: (1) 2.9 eV average resolution (at 5.9 keV) in 16-row TDM (see attached figure); (2) 2.3 eV average resolution at the Al Ka line (1.5 keV) in 32-row TDM, and our first demonstration of 16-row and 32-row CDM readout of X-ray microcalorimeters.

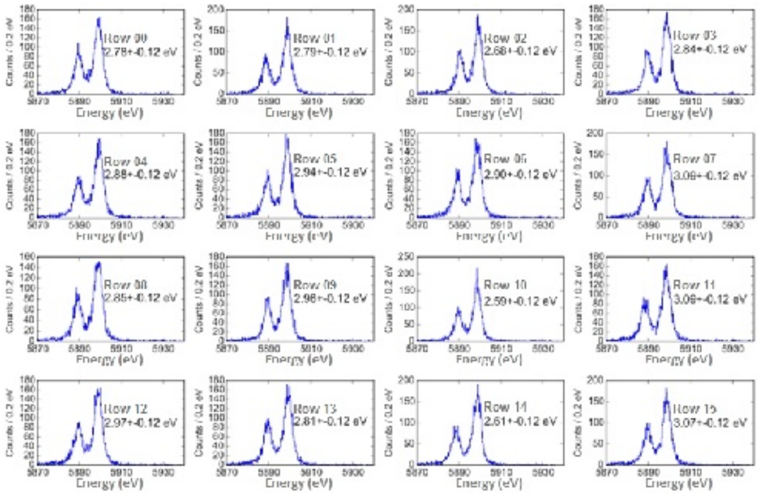

Figure:
TES X-ray spectra of the Mn Kα complex. The 16 TESs are read out via a 16-row time-division multiplexer. The average multiplexed energy resolution across the array is 2.87 eV (FWHM) at 5.9 keV. The non-multiplexed energy resolution of these 16 sensors is ~2.5 eV. The degradation in energy resolution from non-multiplexed to multiplexed readout is well understood in terms of aliased SQUID noise and part-per-thousand-level inductive crosstalk among the readout elements. The row-dwell time is 320 ns. Our next development milestones are to decrease the row time toward 160 ns and improve the system noise, which will allow similar performance in 32 row TDM readout.