Expanding the capability of microwave multiplexed readout for fast signals in microcalorimeters

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Summary:

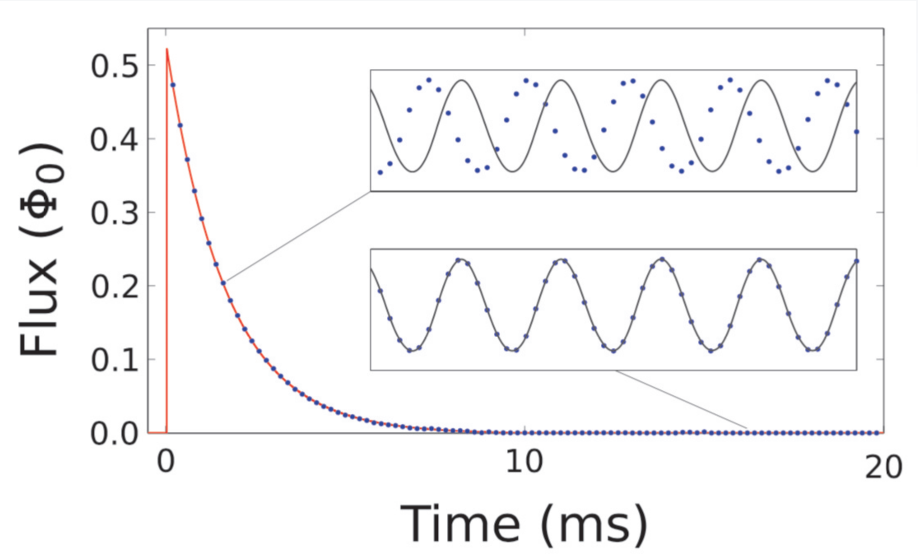
Using our knowledge of microcalorimeter pulse shapes, it is possible to surpass the detector current slew rate "limit" for microwave mux readout by more than a factor of two without degrading energy resolution.

The extra margin can be used to:
- Read out higher energy pulses
- Reduce resonator bandwidth: higher mux factor or less crosstalk
- Increase input coupling to reduce impact of SQUID noise

1 The nominal signal slew rate limit

The SQUID signal is linearized using flux-ramp modulation [1]. The demodulation algorithm measures the phase shift of the flux-ramp response during each ramp: sampling rate = flux-ramp rate (f_r).

[1] Mates et al., J. Low Temp. Phys., 167, 707 (2012)



For an unknown signal, it's impossible to distinguish a phase shift of > π from < -π. So, the nominal limit on current slew rate (in A/s) between samples is:

$$\Phi_0 f_r / 2M_{in}$$

where Φ_0 is the magnetic flux quantum, and M_{in} is the SQUID input coupling strength.

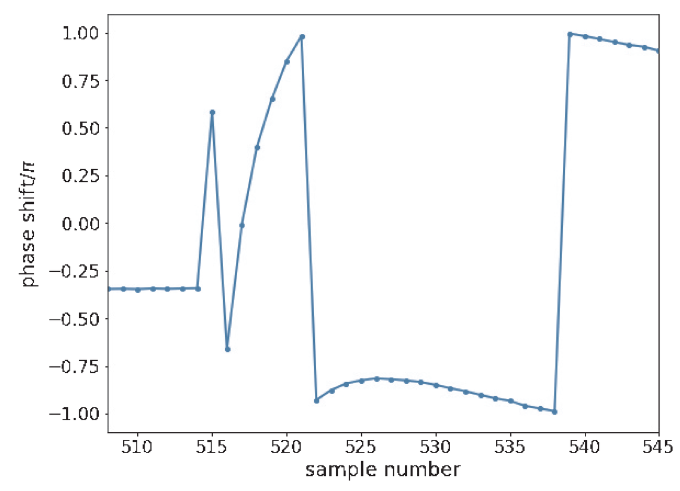
2 Demodulating pulses that exceed the "limit"

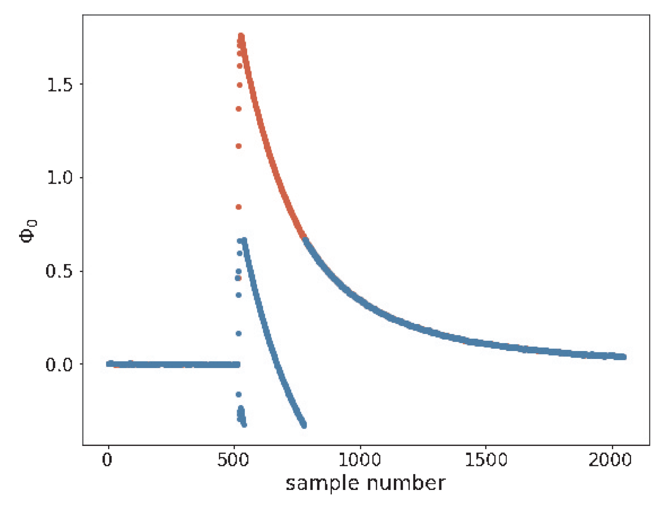
If didn't know what the signal should look like, then the slew rate limit would be strictly $\Phi_0 f_r/2M_{in}$. However, during a pulse, we know which way the current is slewing. So, we can correct pulse events where the phase shift is greater than π, or even greater than 2π.

We make two assumptions:
1. The flux-ramp response is linear; if the phase shift is > π, then the value reported by the demodulation algorithm is correct modulo 2π
2. The slew rate is greatest at the start of the pulse and decreases until the peak

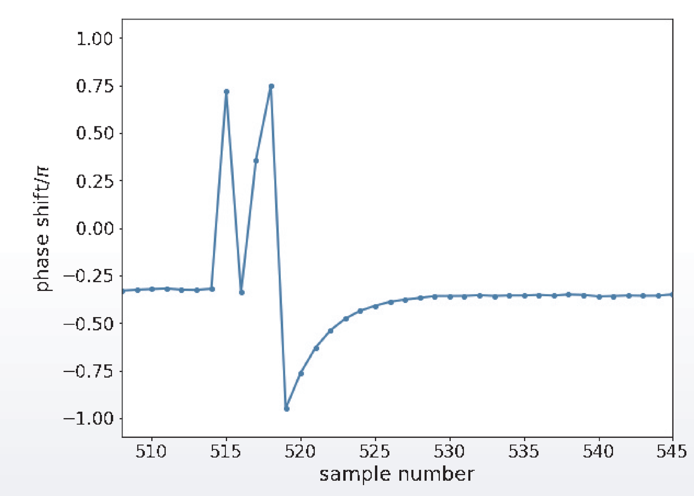
3 Biased unwrapping

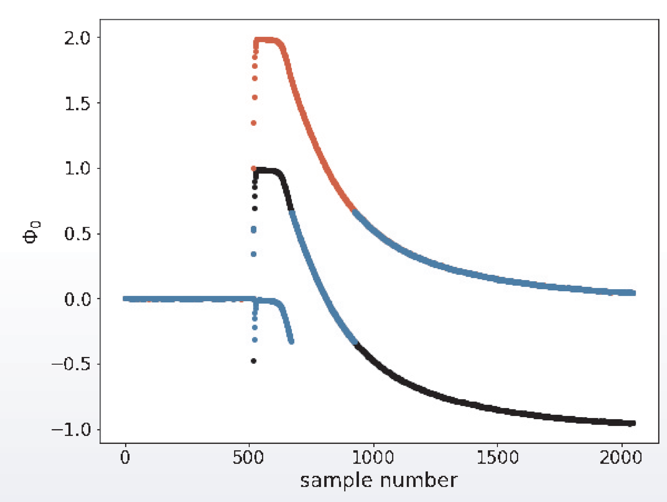
The demodulation algorithm reports a phase shift for each ramp period between -π and π. A pulse may traverse more than 2π (more than 1 Φ_0), so the data are unwrapped before being sent to a software client that collects and stores pulse data.





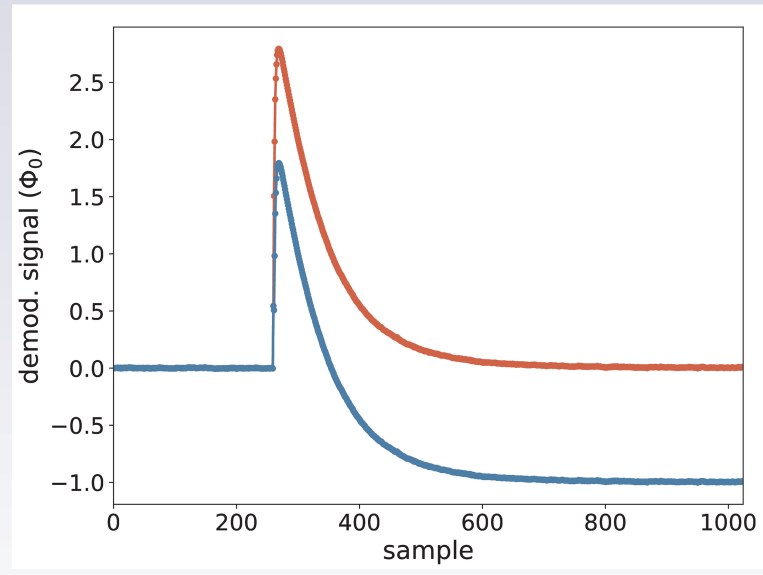
Standard unwrapping: if consecutive samples differ by a phase shift of >π, shift the data down by 2π. If they differ by <-π, shift up by 2π. Left: raw data after demodulation. Right: before (blue) and after (red) unwrapping. The max phase shift is <π, so demodulation succeeds.



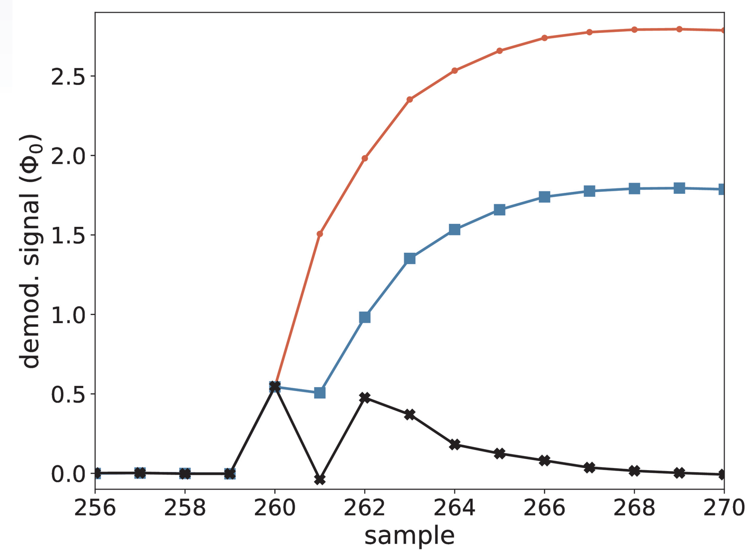


Biased unwrapping: For phase shifts >π, standard unwrapping may shift data in the wrong direction (black trace). But, during a pulse the largest phase shift occurs on the rising edge. So, we "bias" the unwrapping algorithm: if the ratio of falling edge to rising edge slew rate is X, shift differences of >2(1-X/2)π by -2π, and differences <-Xπ by +2π. The effective slew rate limit is $(1-X/2)\Phi_0 f_r/2M_{in}$.

4 Correction using pulse records



If the falling edge slew rate is < $\Phi_0 f_r/2M_{in}$, the demodulation algorithm correctly tracks the falling edge. Then, identifying events that need correction is easy: after the pulse, the baseline drops 1 Φ_0 below the pre-trigger baseline (blue trace).

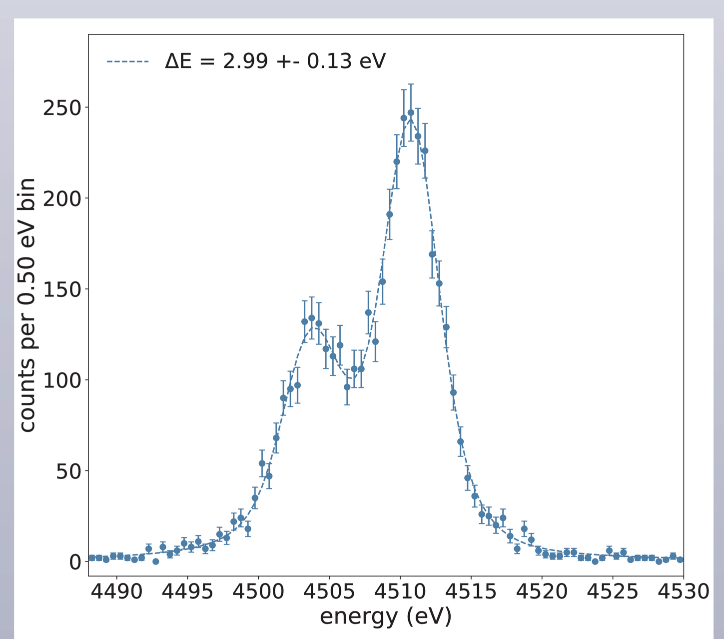


Identify which sample in the original pulse record (blue) needs correction: the difference between consecutive samples (black) should be largest after the trigger and decrease until the pulse peak because the slew rate is highest at the start of a pulse. In this example, the error has occured at sample 261. We correct the pulse by adding $1\Phi_0$ to samples after #260 (red).

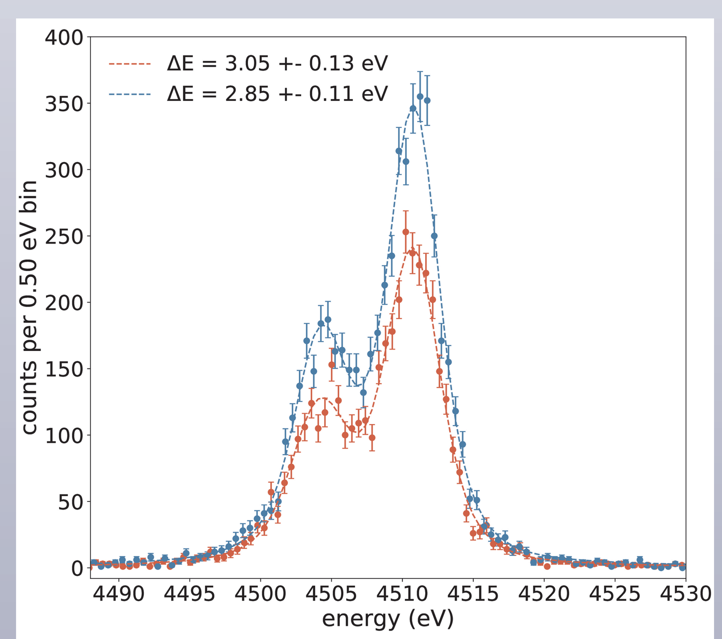
5 Okay...but does it work?

A Mo/Au bilayer TES was used to measure Ti Ka x-rays (4.51 keV).
More on Mo/Au TES development: J. Weber, Orals LM 003: FAB, 24 July 2019, 12:15

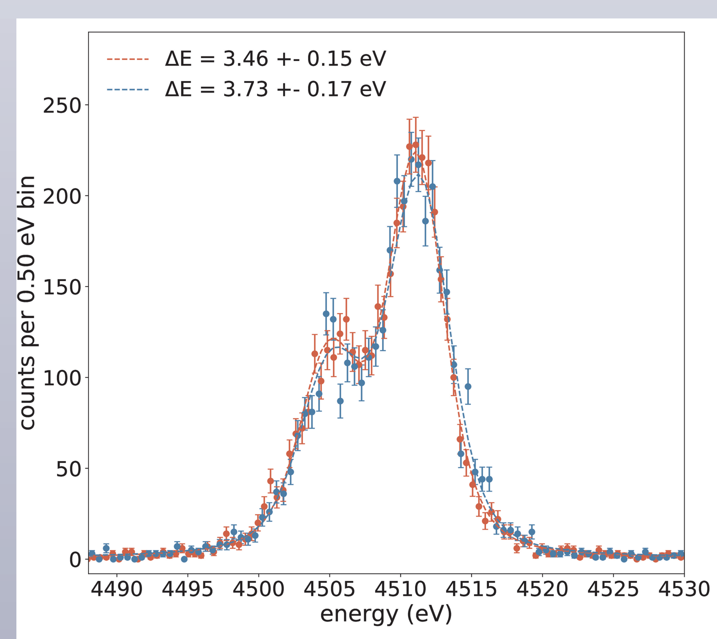
Resonator bandwidth = 2 MHz. Flux-ramp amlitude = $2\Phi_0$, making the maximum sampling rate 500 kHz.



At f_r = 500 kHz, average max slew rate of Ti Kα = 0.44 Φ_0/sample, no correction is needed. The detector's energy resolution was ΔE = 2.99 ± 0.13 eV FWHM.



Blue: f_r = 250 kHz, avg. max slew rate = 0.8 Φ_0/sample, ΔE = 2.85 ± 0.11 eV FHWM.
Red: f_r = 500 kHz data downsampled to 250 kHz, ΔE = 3.05 ± 0.11 eV.



Blue: fr = 125 kHz, avg. max slew rate = 1.36 Φ_0/sample, ΔE = 3.73 ± 0.17 eV.
Red: data downsampled from 500 kHz to 125 kHz, ΔE = 3.46 ± 0.15 eV, suggesting degradation can be accounted for primarily by arrival time effects induced by undersampling the rising edge.

Experimental Result:

We show demodulated pulses with slew rates up to 2.7x the nominal $\Phi_0 f_r/2M_{in}$ limit for microwave mux readout, using a practical alogrithm to reconstruct events that are incorrectly demodulated. The impact on energy resolution is minimal, but undersampling the rising edge can still degrade performance, independent of whether or not the slew rate exceeds the nominal limit. As long as the sampling rate is adequate, the extra slew rate margin could be used to increase mux factor, reduce crosstalk or noise, or read out higher energy pulses.

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