Crosstalk and pile-up rejection in microwave SQUID multiplexers

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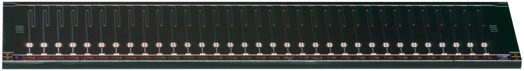
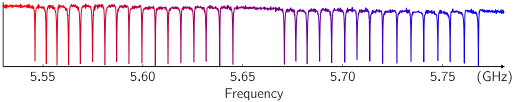
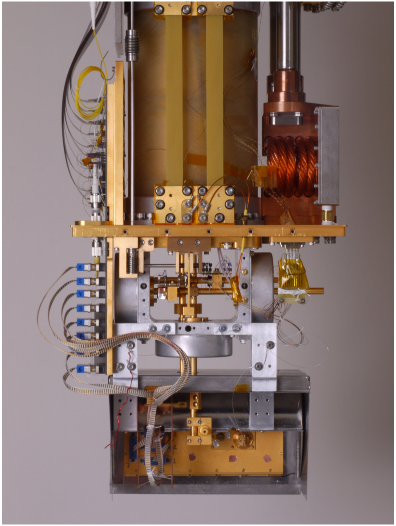
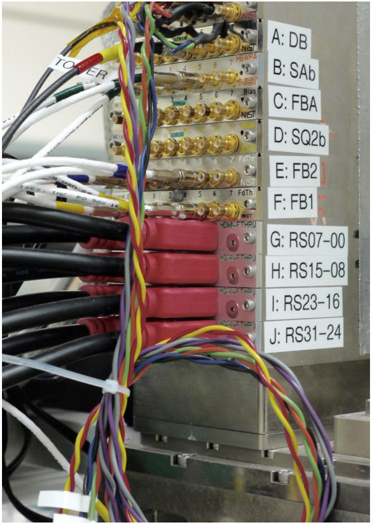




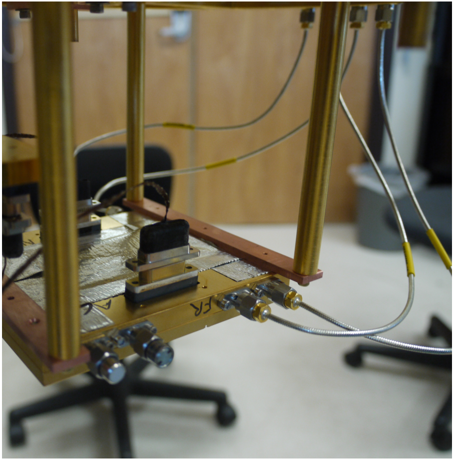
Time-division SQUID multiplexing (TDM)

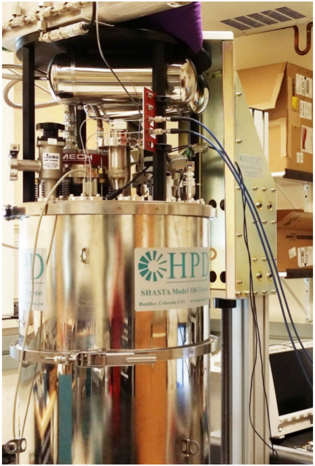




∼200 wires to read out ∼250 pixels

Microwave SQUID multiplexing (μmux)

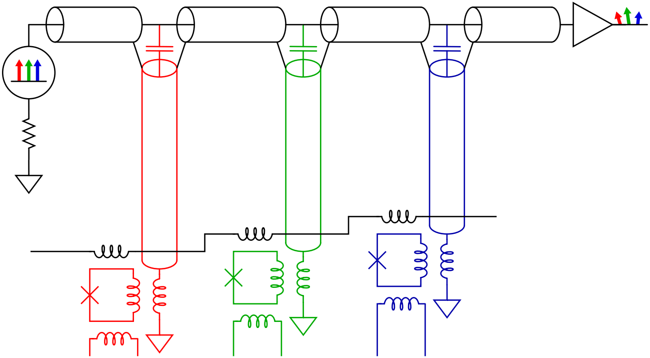




2 coaxial cables + 2 low-frequency pairs to read out ~250 pixels

μmux Concept

Non-hysteretic rf-SQUIDs modulate non-overlapping resonators



μmux Concept

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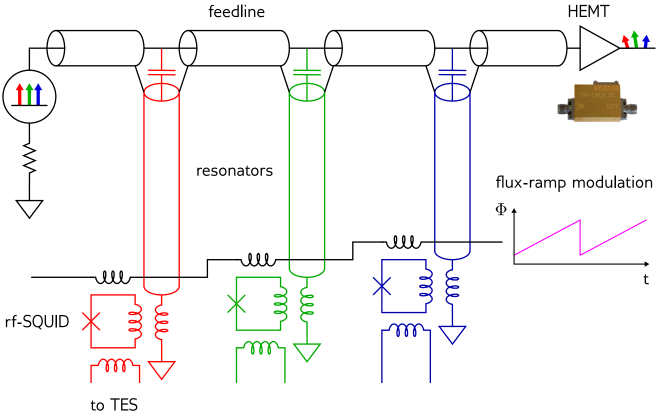
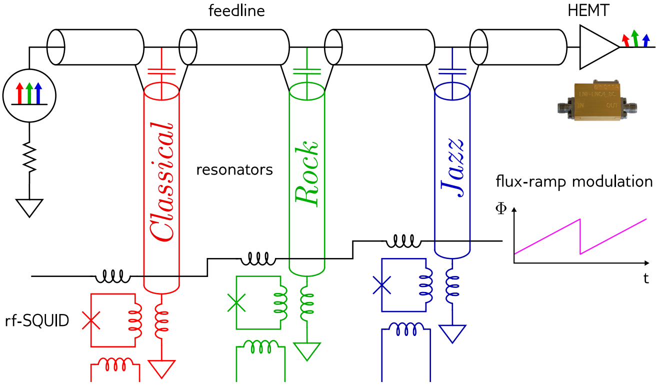
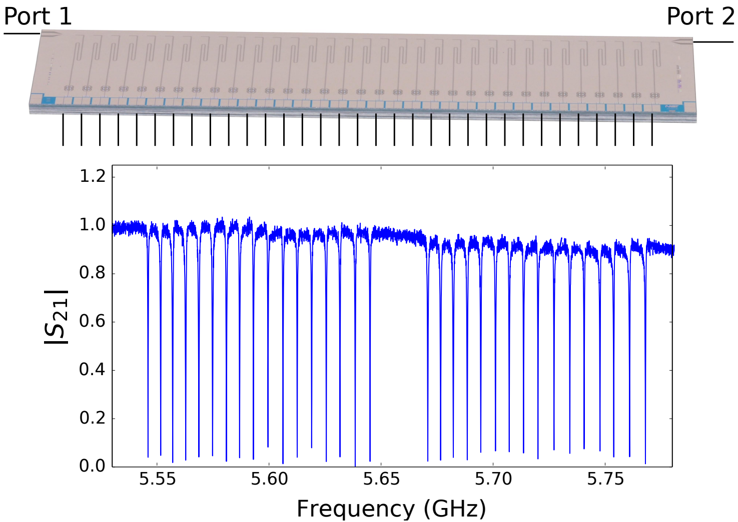


Non-hysteretic rf-SQUIDs modulate non-overlapping resonators

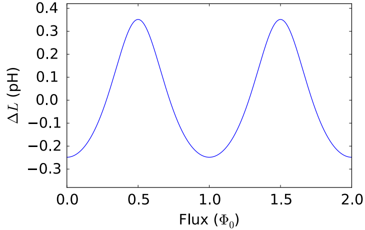


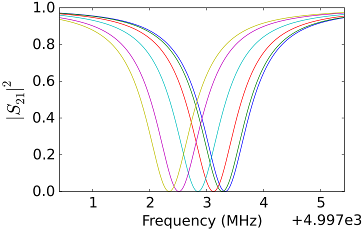
Read out large array with two coax + handful of DC lines

μmux Concept



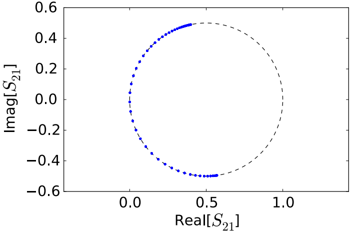
μmux Output Chain



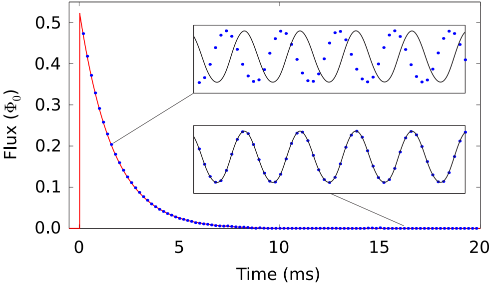


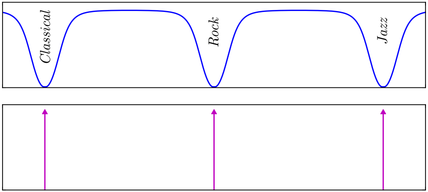
Output chain

1. Flux in an rf-SQUID modulates its inductance
2. SQUID inductance modulates resonance frequency of its resonator
3. Resonance frequency modulates transmission of fixed microwave tone



- Linear flux ramp applied to all SQUIDs in multiplexer
- Encodes flux in the phase of the SQUID response
- Effectively linearizes SQUID readout
- Up-mixes signal above low-frequency two-level system (TLS) noise in resonators





Flux-ramp modulation

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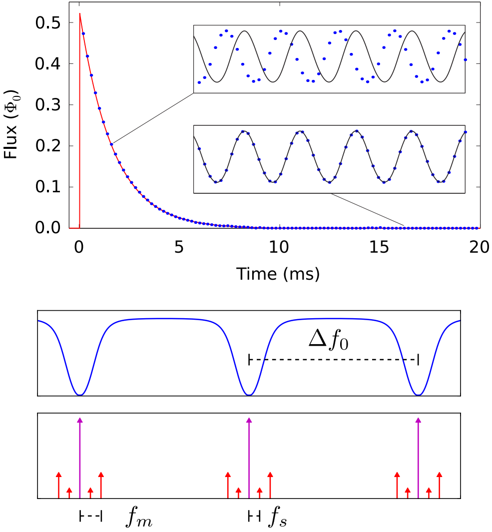
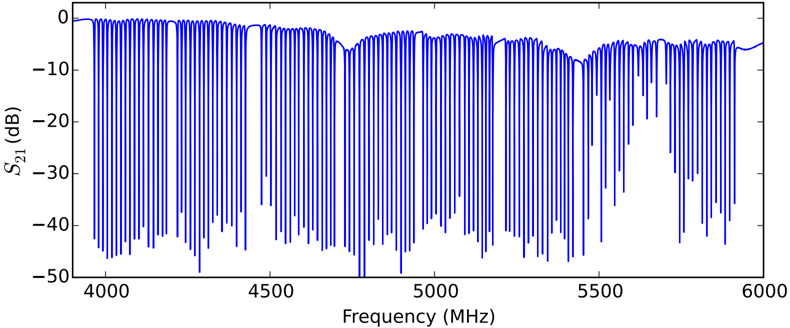


μmux Measurements: Resonance Spacing

Design for high-rate calorimetry (e.g. neutrino end-point measurement):

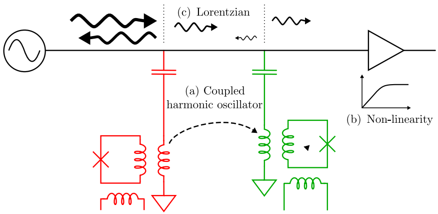
- 2 MHz resonator bandwidth
- 14 MHz spacing
  - 64 channels per GHz



Crosstalk mechanisms in μmux

Several mechanisms of crosstalk in the microwave SQUID multiplexer:

a) Coupled simple harmonic oscillator crosstalk
b) Non-linear broadband component crosstalk
c) Lorentzian tail crosstalk



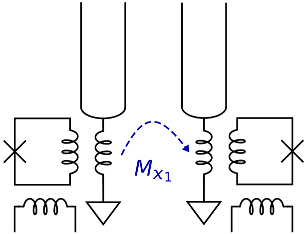
Crosstalk mechanism: coupled harmonic oscillators

Parasitic coupling between the resonators hybridizes the natural eigenstates:

$$\begin{bmatrix} \frac{1}{C} + L_1 \frac{d^2}{dt^2} & M_{x_1} \frac{d^2}{dt^2} \\ M_{x_1} \frac{d^2}{dt^2} & \frac{1}{C} + L_2 \frac{d^2}{dt^2} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} e^{-i\omega t} = 0$$

$$\Rightarrow \omega = 1/\sqrt{C\left(\frac{L_1+L_2}{2} \pm \sqrt{\frac{L_1-L_2}{2} + {M_{x_1}}^2}\right)}$$

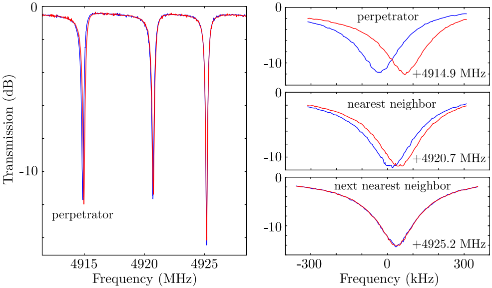
$$\chi \approx \frac{1}{4} \frac{\bar{\omega}^2 {M_{x_1}}^2}{{Z_0}^2} \frac{\bar{\omega}^2}{(\omega_1-\omega_2)^2} \propto \boxed{\frac{{M_{x_1}}^2}{(f_1 - f_2)^2}}$$



Crosstalk mechanism: coupled harmonic oscillators

- Simulated and observed crosstalk follow predicted scaling with ${M_{x_1}}^2$ and $(f_1 - f_2)^{-2}$
- Typical coupling between physical neighbors of:
  - $\frac{\omega M_{x_1}}{Z_0} \approx 10^{-4}$
- Typical splitting between frequency neighbors of:
  - $\frac{\omega}{\omega_1 - \omega_2} \approx 10^3$
- Solved by interleaving resonance frequencies!

example of bad coupled S.H.O. crosstalk



Broadband nonlinearity: IP3

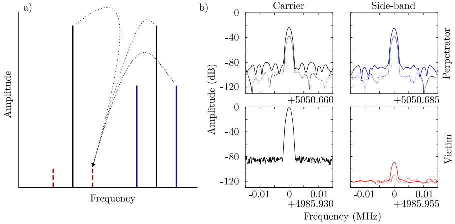
- Broadband devices in the readout chain not perfectly linear:

  $$V_{out} = G_0 + G_1 V_{in} + G_2 {V_{in}}^2 + G_3 {V_{in}}^3 + \ldots$$

- Relevant non-linearity can be quantified by $IP3$, the intercept of the 3rd-order intermodulation products with the fundamentals:

  $$IIP3 \equiv \frac{2|G_1|}{3|G_3|Z_0}$$

  (input-referred)



Broadband nonlinearity: theory and measurement

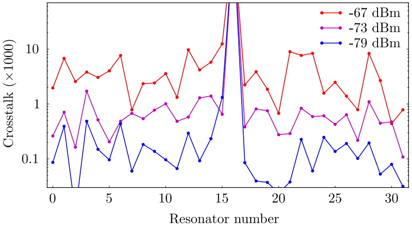
- 3rd-order intermodulation products transfer modulation from one carrier to another:

$$f_1 \times (f_1 + f_m) \times f_2 \rightarrow f_2 + f_m$$

- Crosstalk depends on power:

$$\boxed{\chi \approx \frac{4P_{\mathrm{perp}}}{IIP3}}$$

- Weak crosstalk from every channel into every other channel!
- Solved with high $IIP3$ components.

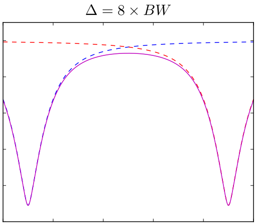


Lorentzian tail: design constraint

- Long tail of each resonator's response affects its frequency neighbors
- Set by number of bandwidths apart:

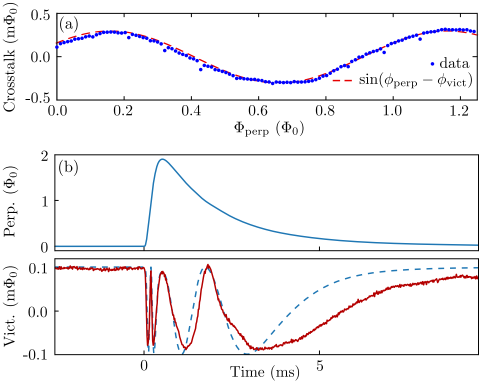
$$\chi \approx \frac{1}{16(\Delta/BW)^2}$$

- Roughly 7-8 bandwidths apart for part-per-thousand crosstalk
- Fundamental limit on multiplexing factor!

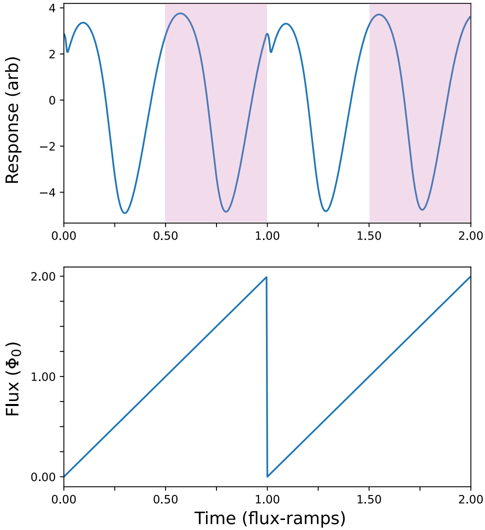


Post-SQUID-modulation crosstalk

- Crosstalk occurs between flux-ramp-modulated signals
- Results in sinusoidal crosstalk after phase demodulation
- Amplitude determined by χ parameters

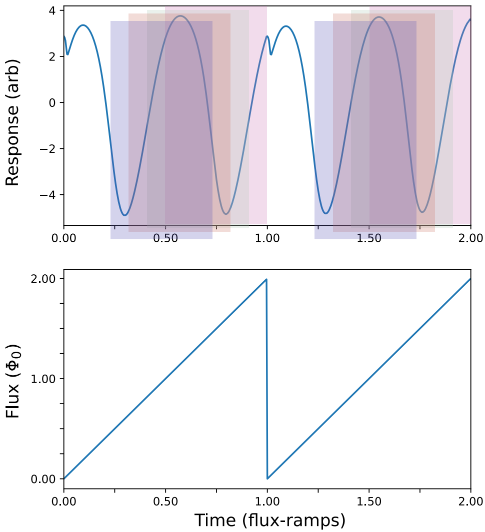


- Currently demodulate in fixed windows of clean data
- One sample of the detector signal per flux-ramp period
- Pile-up events must be at least one flux-ramp period apart to be rejected

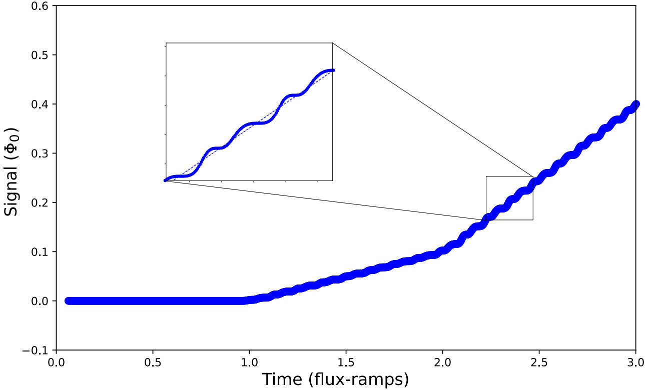


Flux-ramp demodulation

- Can demodulate in multiple overlapping windows
- Multiple (correlated) samples of the detector signal per flux-ramp period
- Possibility of rejecting closer pile-up events

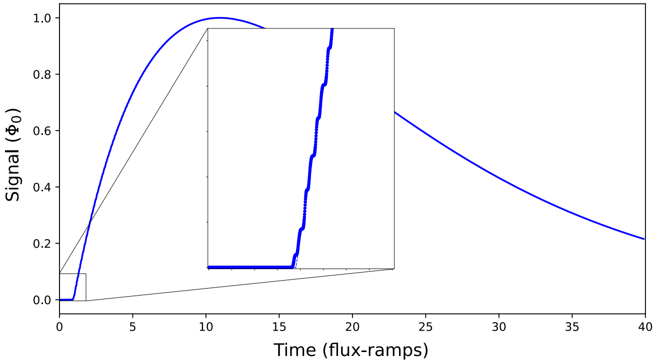


Sub-flux-ramp demodulation



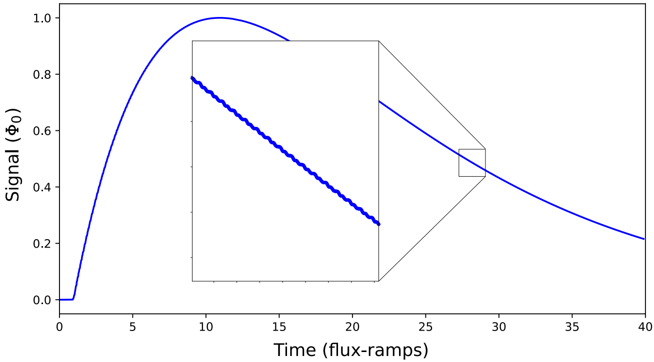
Sub-flux-ramp demodulation shows small oscillations proportional to signal slew-rate

Sub-flux-ramp demodulation



Oscillations vanish at baseline and peak of pulse

Sub-flux-ramp demodulation



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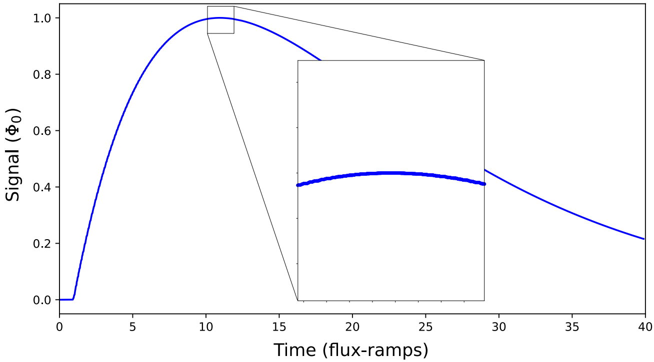
Sub-flux-ramp demodulation



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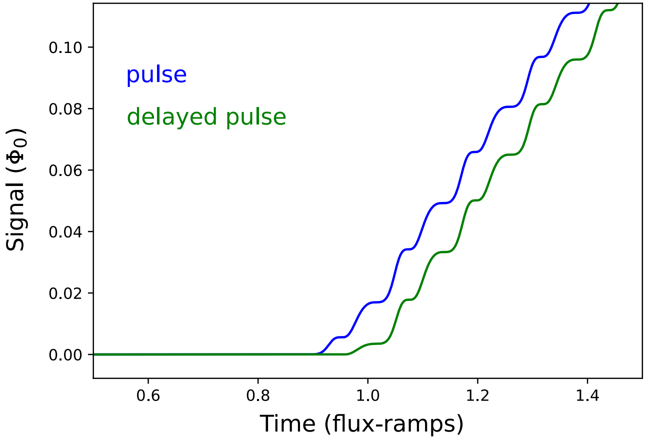
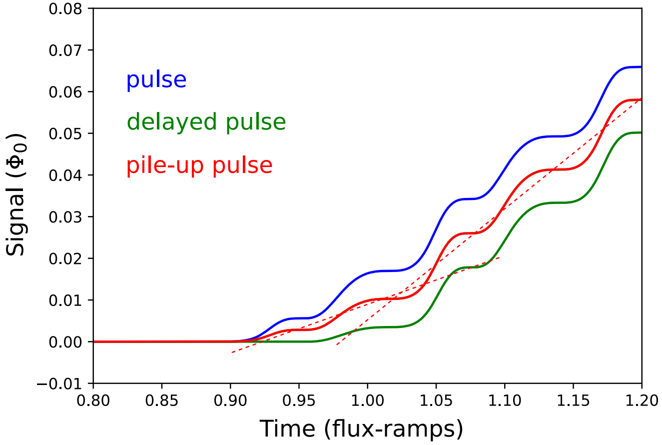


However, it is still possible to identify pulse arrival time with sub-flux-ramp accuracy

Sub-flux-ramp demodulation



And it is potentially possible to detect pile-up events closer than a flux-ramp period

Conclusion

- Microwave SQUID multiplexer provides necessary bandwidth for neutrino mass end-point measurements
- Requires careful design to minimize crosstalk between channels
- Sub-flux-ramp information may allow better pile-up rejection