Microwave SQUID multiplexers with scalable readout

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July 21, 2015

Motivation

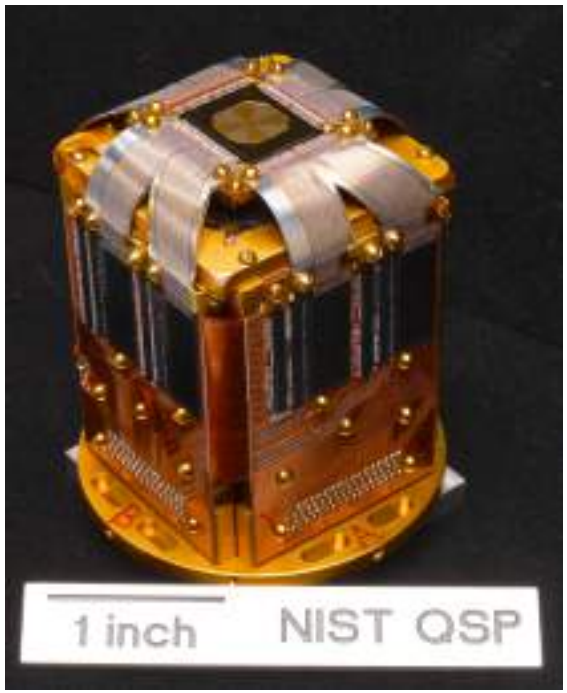
Increase total readout bandwidth:

- Some applications need more bandwidth / pixel
- Some require more pixels

Example: x-ray beamline science

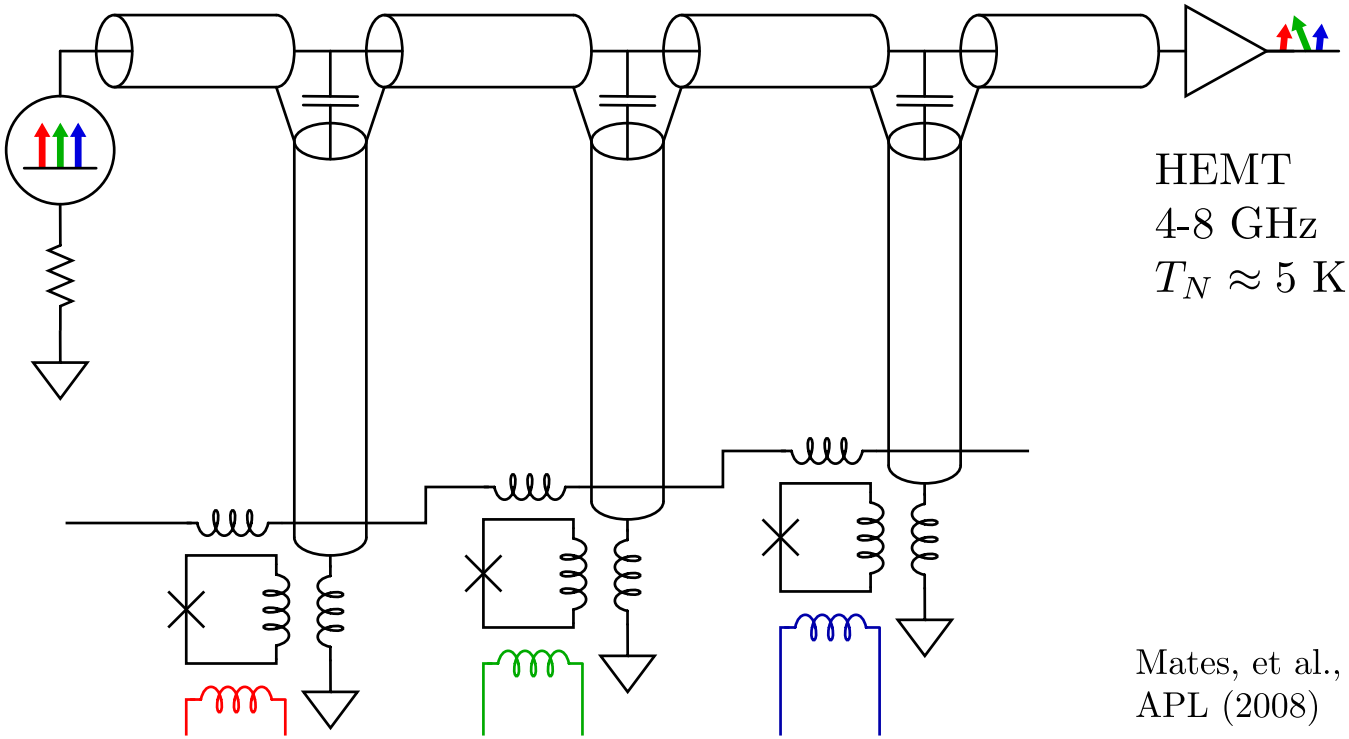
- State-of-the-art: 240 pixels, 100 kHz sampling
- Desired: ∼10 kilopixels, ∼1 MHz sampling

Bandwidth demands ⇒ GHz frequencies



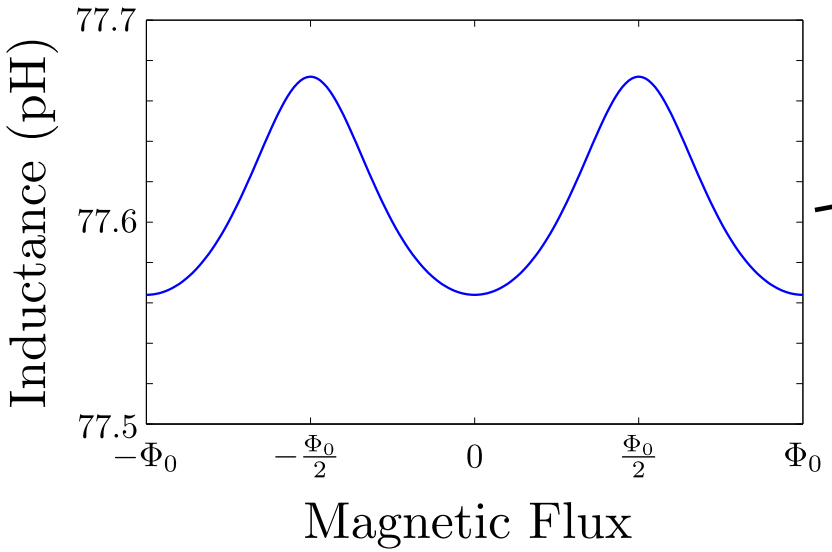
μmux concept

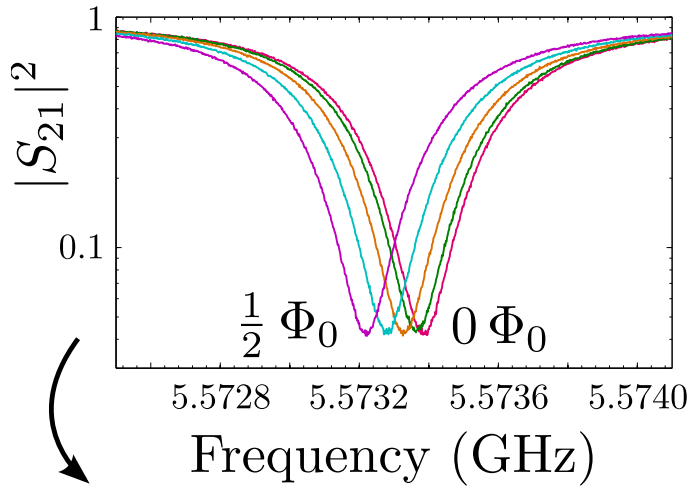
Dissipationless rf-SQUIDs modulate non-overlapping resonators

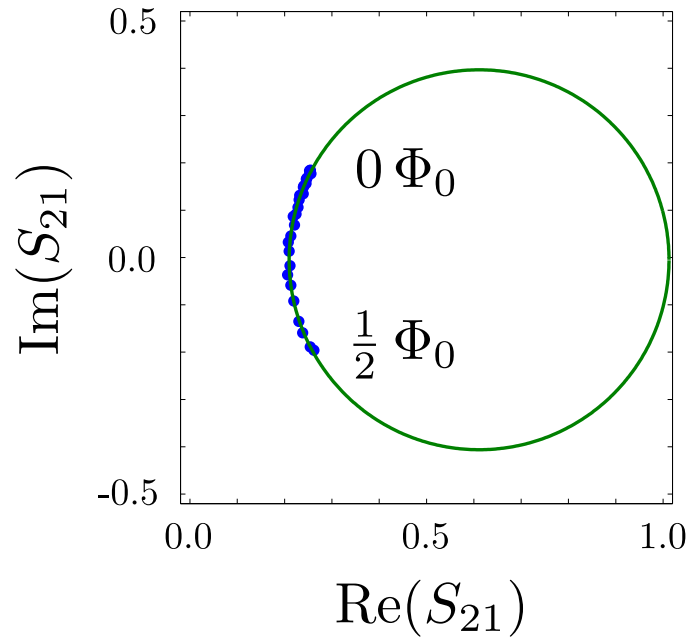


Can read out large array with two coax + handful of DC lines

μmux details







Output chain:

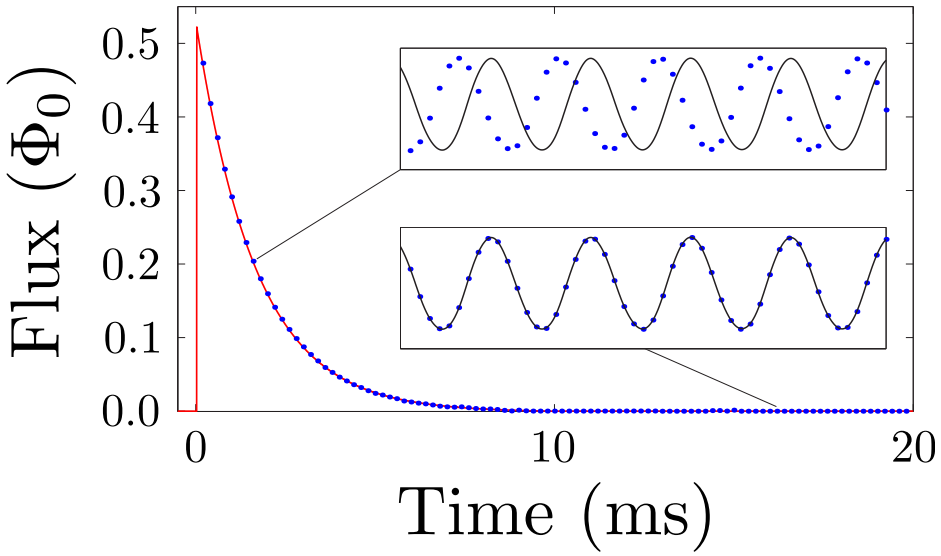
1. Flux in an rf-SQUID modulates its inductance
2. SQUID inductance modulates resonance frequency of its resonator
3. Resonance frequency modulates transmission of fixed microwave tone

μmux flux-ramp

We use *flux-ramp modulation** to measure the flux in the SQUIDs:

- Linear flux ramp applied to all SQUIDs in multiplexer
- Phase-modulates SQUID response
- Effectively linearizes SQUID
- Upmixes signal above low-frequency two-level system (TLS) noise in resonators

Read out signal phase to measure flux in SQUID



*Mates, et al., JLTP (2012)

μmux theory

- Optimal power to a resonator at $f_0 \approx 6$ GHz:

$$P_{\mathrm{feed}} \approx \frac{p^2}{\eta} \frac{{\Phi_0}^2 f_0}{8 L_{\mathrm{J}} (1-\lambda^2)}^{*} \approx -70 \ \mathrm{dBm}$$

  where $\eta \approx 1$ is the ratio of frequency shift to bandwidth and $p \approx 1/\pi$ is the amplitude of microwave flux in the SQUID

- Predicted flux noise due to HEMT with noise temperature $T_N \approx 6$ K:

$$\sqrt{S_\Phi} \approx \sqrt{\frac{4 k_{\mathrm{B}} T_N L_{\mathrm{J}}}{\pi f_0}}^{*} \approx 0.5 \ \mu\Phi_0/\sqrt{\mathrm{Hz}}$$

  which is degraded approximately 2$\times$ by addition of other noise sources (e.g. TLS noise) and 2$\times$ by flux-ramp modulation $\Rightarrow \sim 2 \ \mu\Phi_0/\sqrt{\mathrm{Hz}}$

* Mates, Thesis, 2011

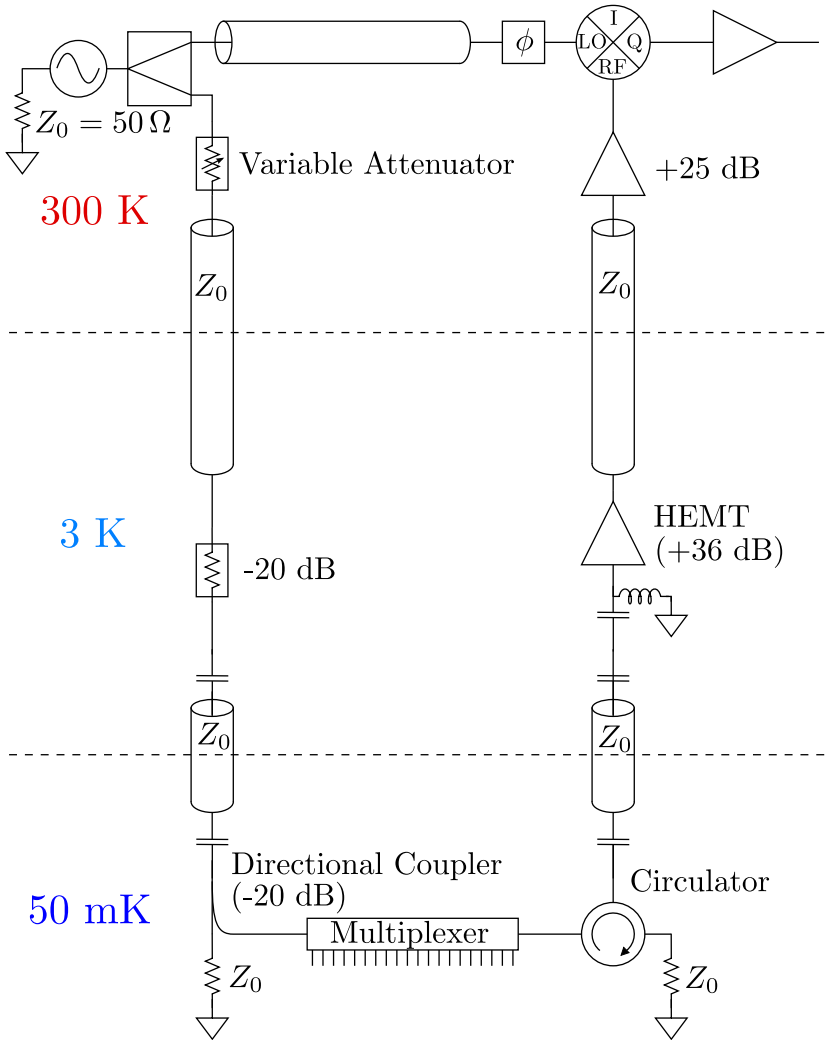
Homodyne readout

μmux developed using homodyne readout:

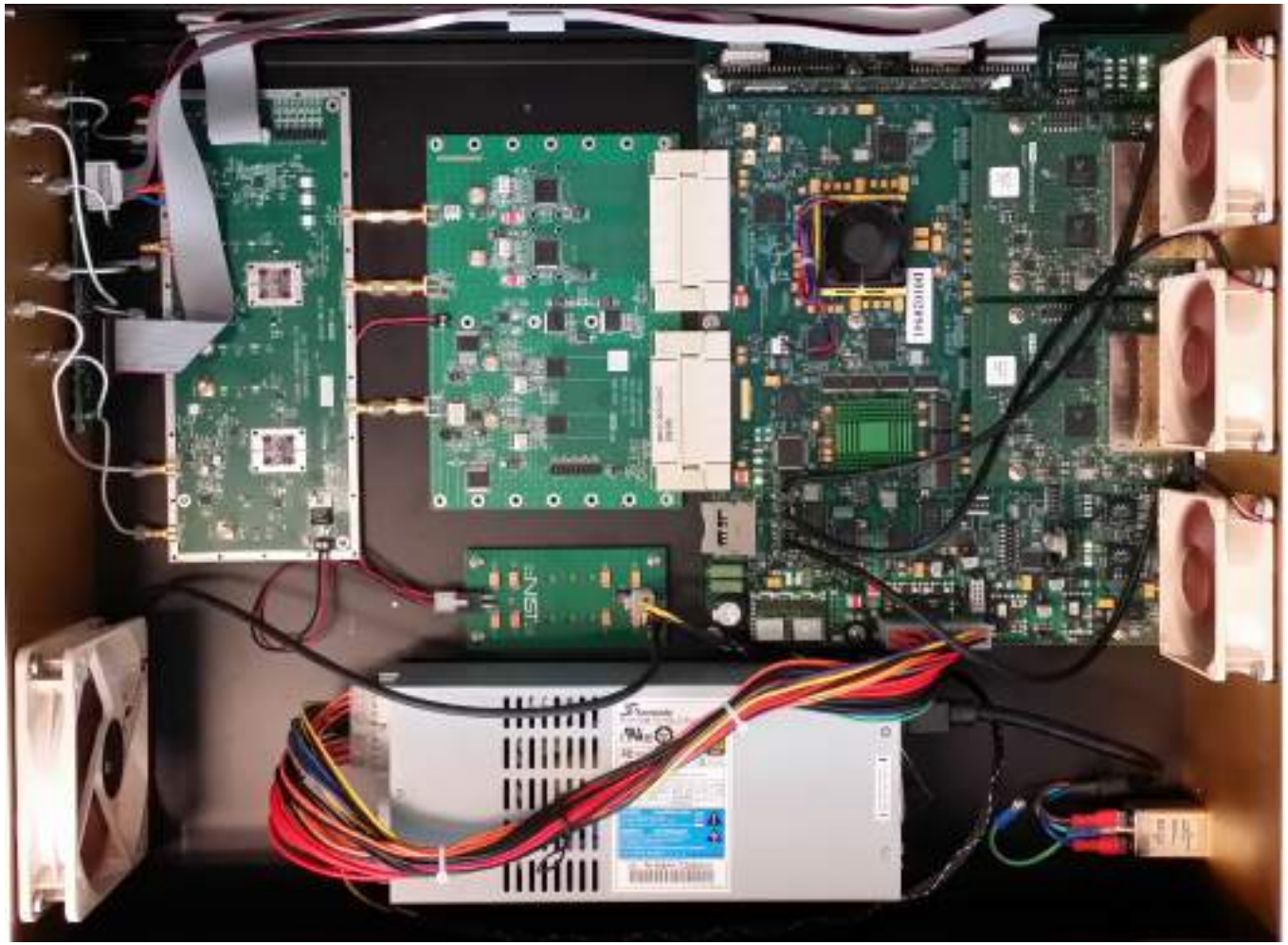
1. Microwave synthesizer generates single tone
2. Tone is split into two branches
   - One branch passes through cryostat
   - One branch preserved for reference
3. Branches combine in IQ-mixer to measure complex transmission

Homodyne readout demonstrated*, but not scalable to large arrays

*Noroozian, et al., APL, (2013)



ROACH-2

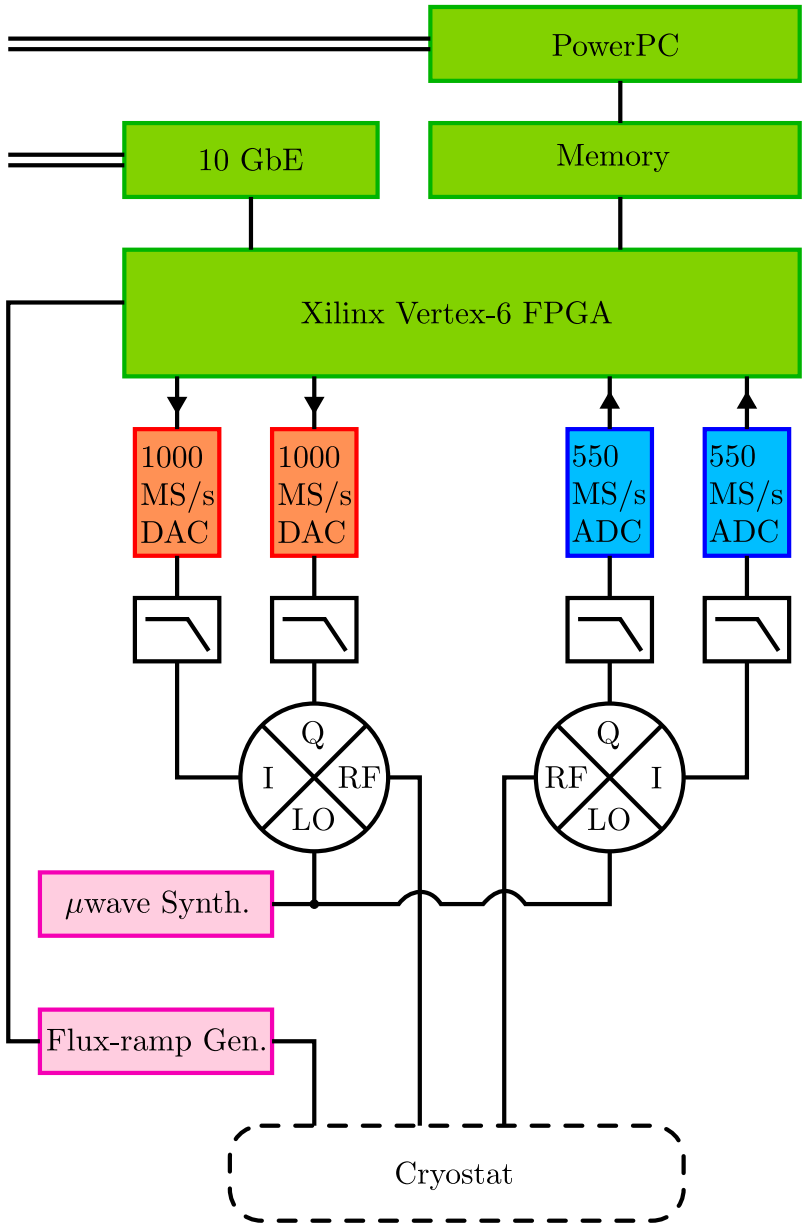


We use the Reconfigurable Open-Architecture Computing Hardware rev. 2 (ROACH-2) to digitally measure many microwave tones simultaneously

Software-defined radio

We use the ROACH-2 platform to perform Software-Defined Radio (SDR):

- Digitally synthesizing a superposition of baseband tones
- Mixing up to microwave frequencies and back down after the cryostat
- Digitally capturing the superposition of modulated tones at baseband
- Processing the data in firmware to separate it into readout channels

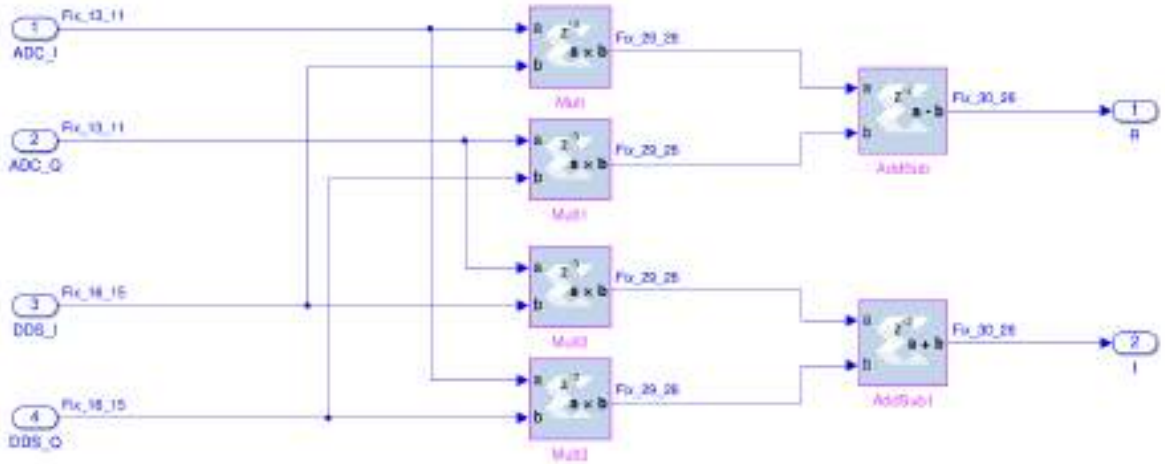


ROACH-2 firmware

μmux firmware must:

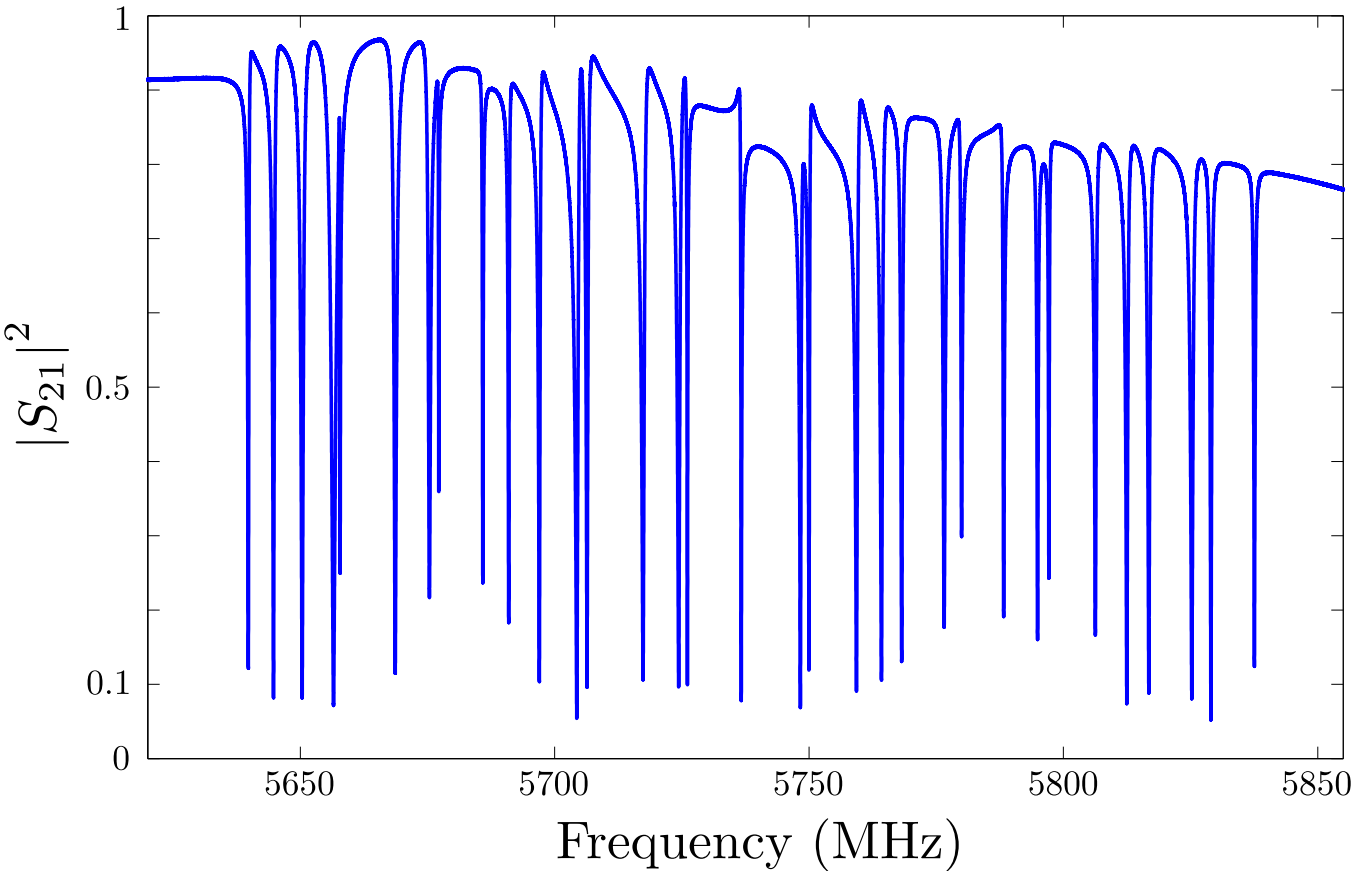
- Generate baseband probe tones
- Separate measured tones into channels
- Extract angles on resonance circles
- Phase-demodulate flux-ramp responses
- Packetize data for upload

See Jonathon Gard's poster Weds. for details!



μmux14b

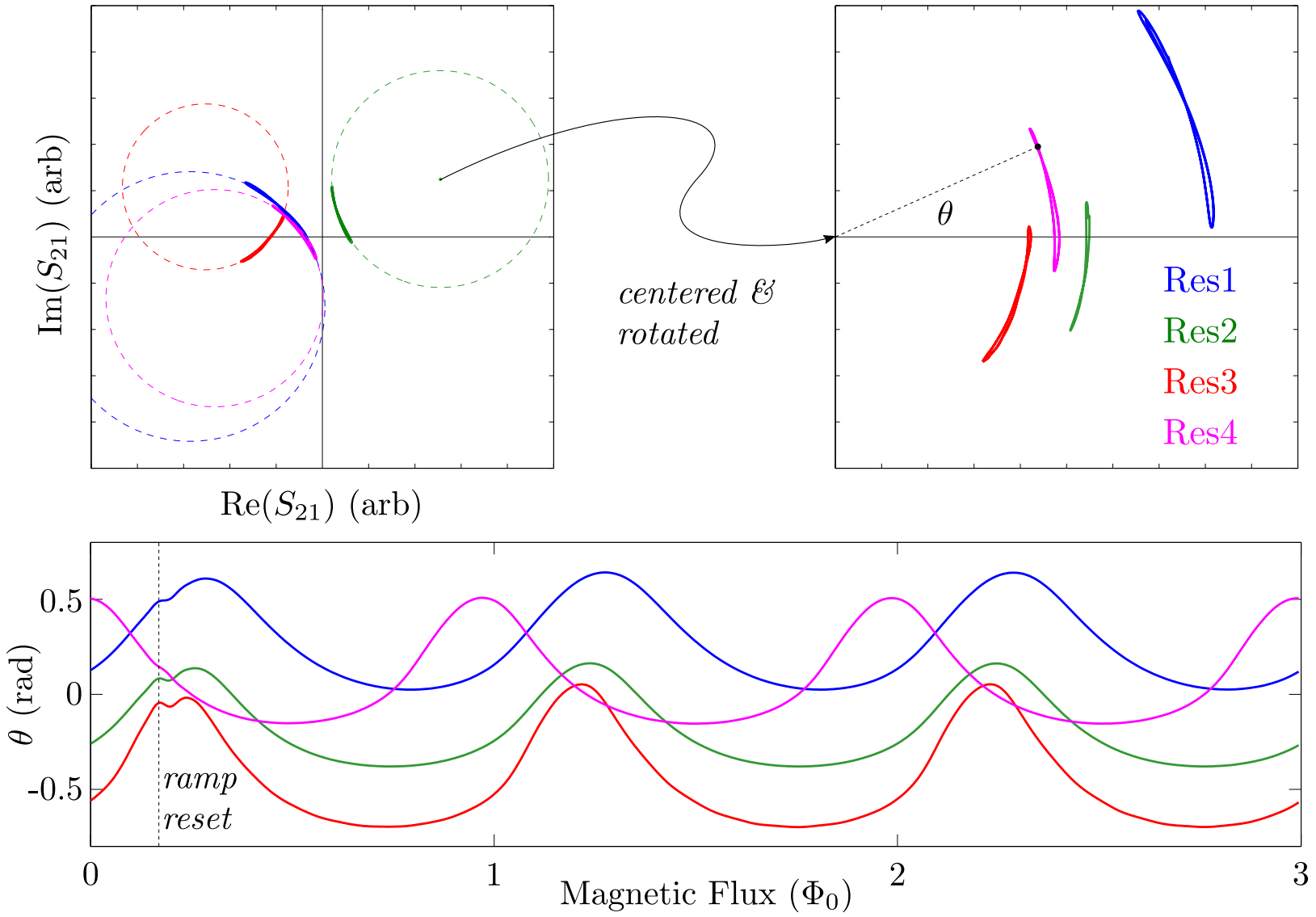
We measured subsets of a 33-channel μmux14b chip



Design parameters: $M_{\text{in}} = 232$ pH, $BW \approx 350$ kHz / channel, $\Delta f_0 \approx 6$ MHz

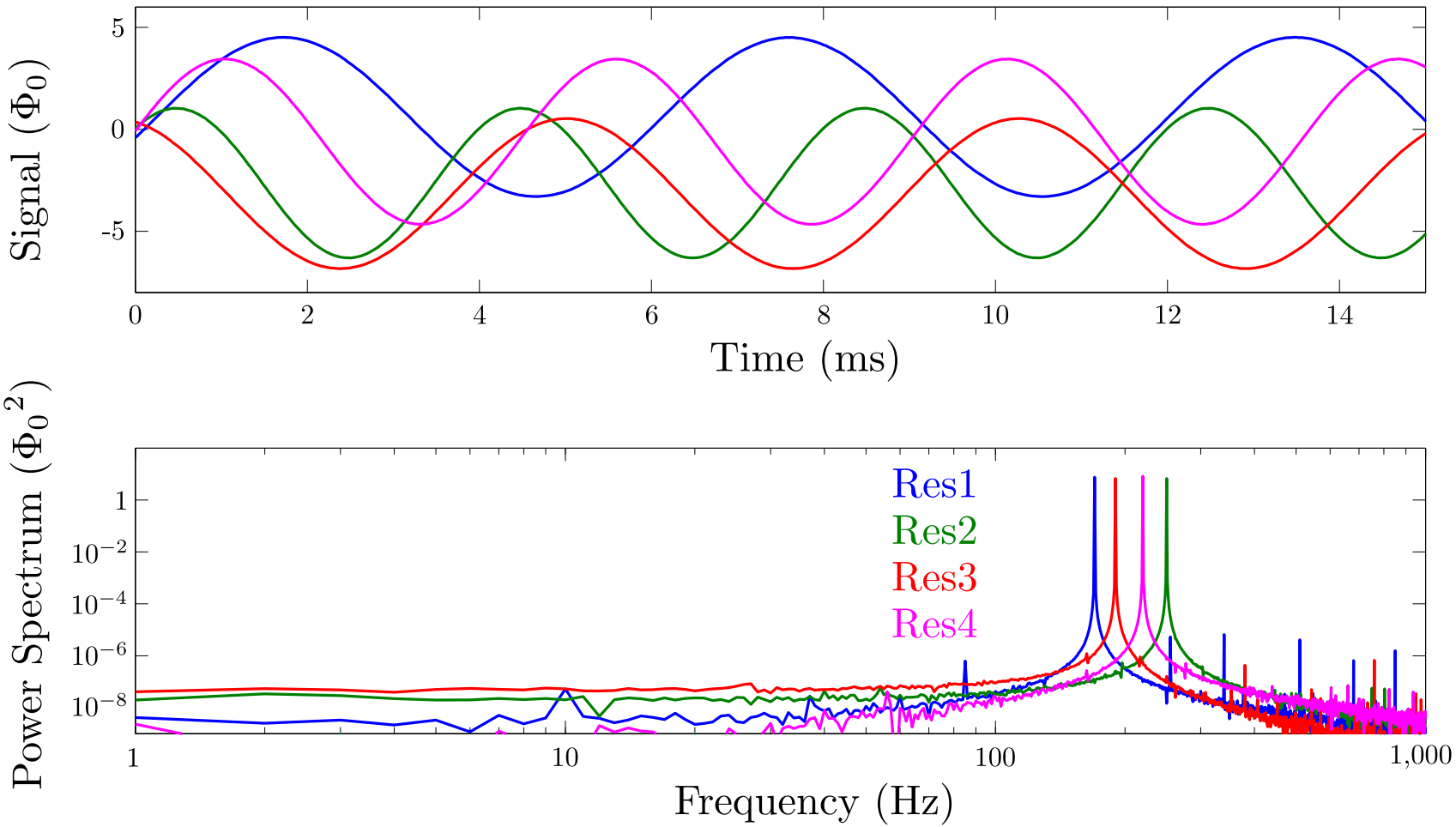
ROACH-2 readout: resonator response

Simultaneously measured resonances modulated along their resonance circles



ROACH-2 readout: flux-ramp demodulation

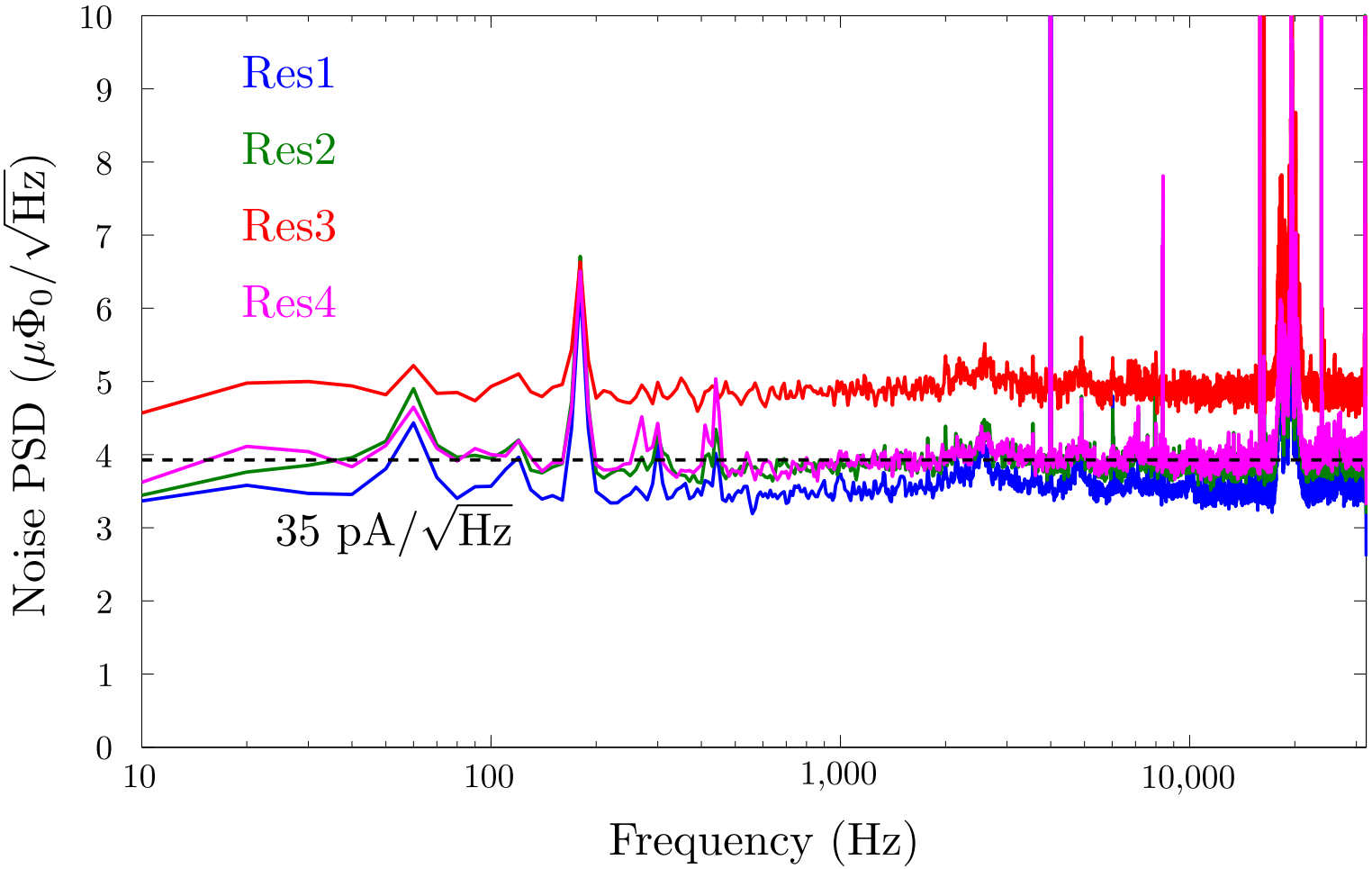
Corresponding SQUIDs fed with different input sine waves, extracted signals:



Flux-ramp demodulation recovers signals with high fidelity, low crosstalk

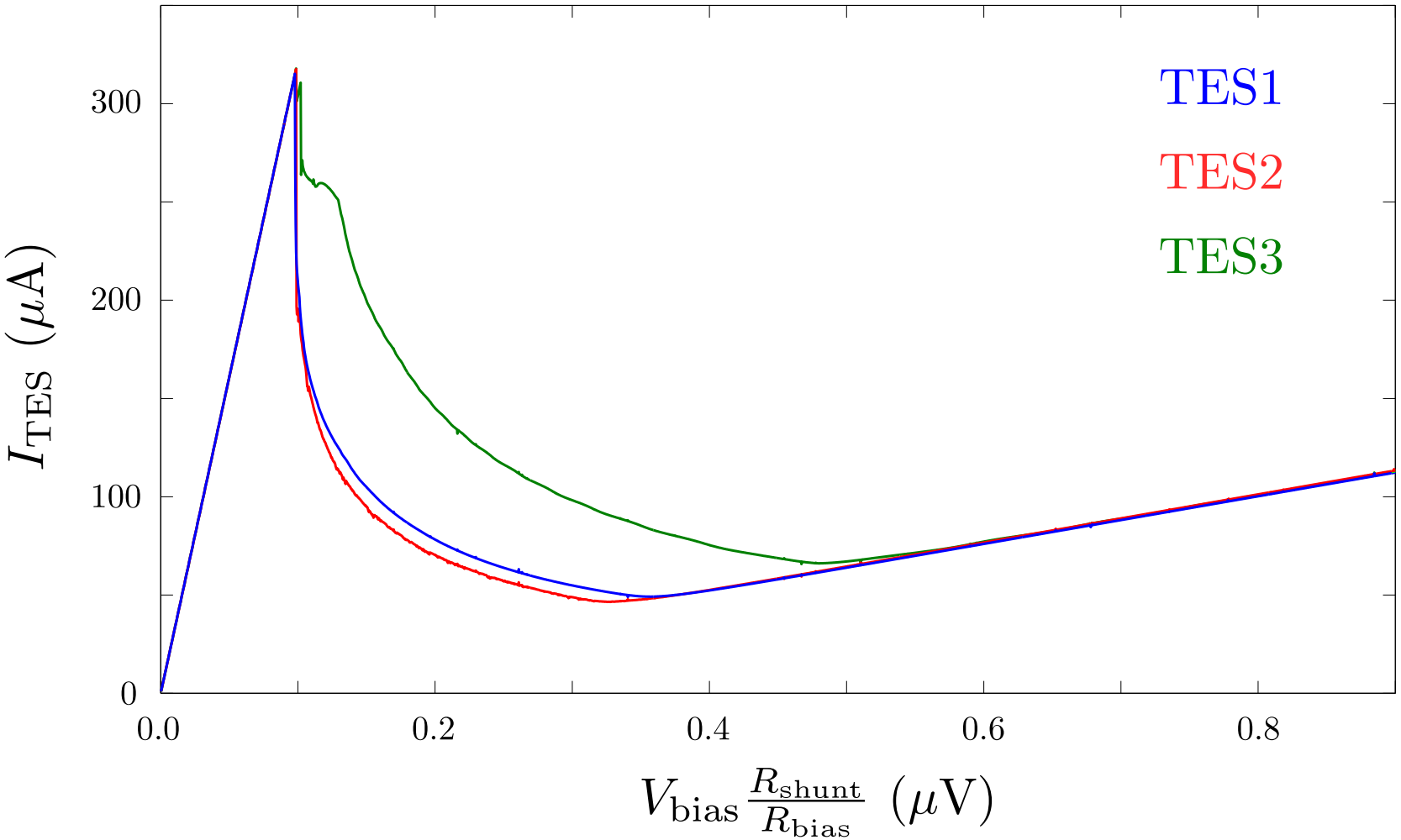
ROACH-2 readout: noise

Noise of four SQUIDs with no input signals



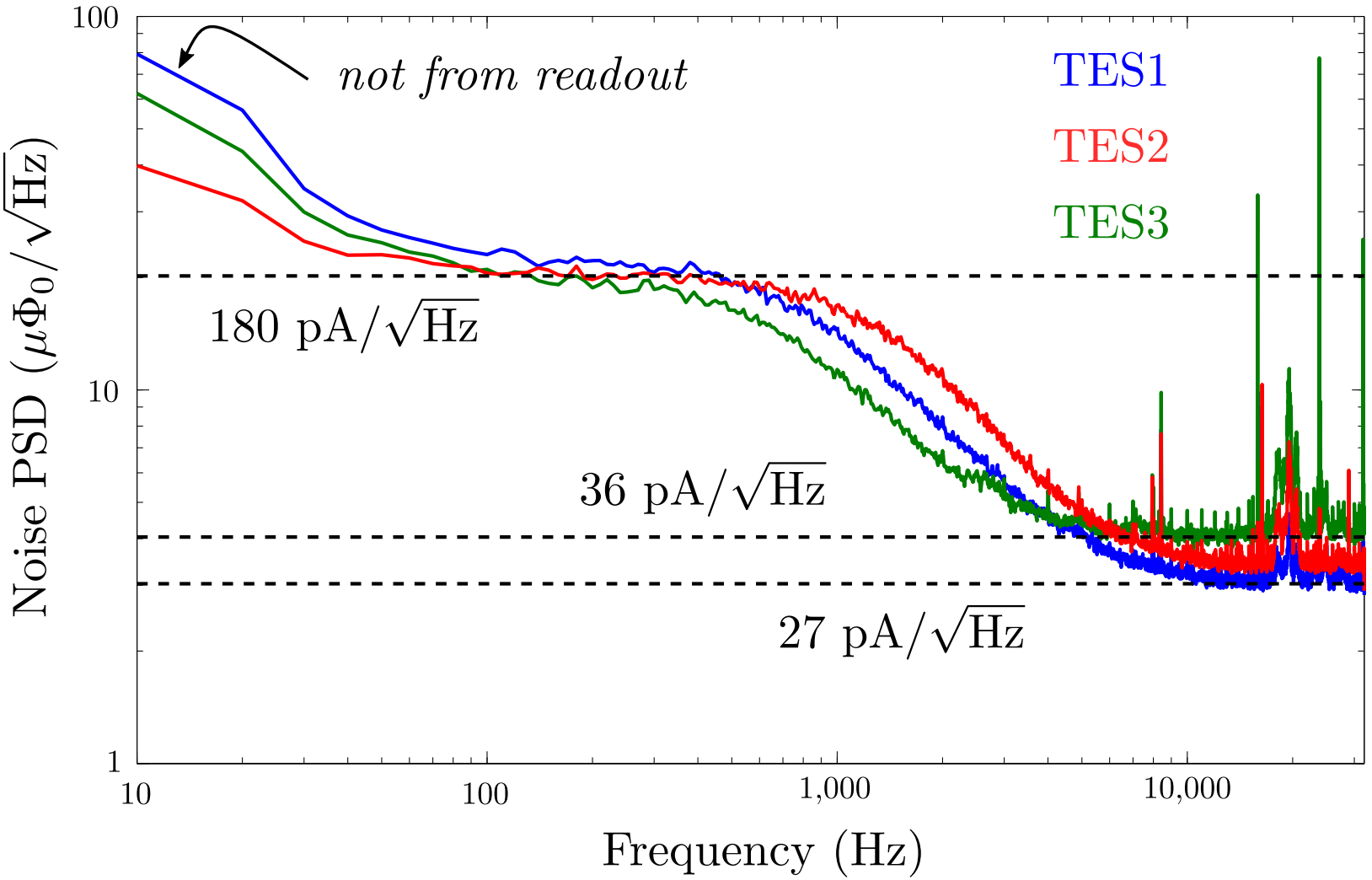
Noise not degraded relative to homodyne readout - sufficient for most TES applications

ROACH-2 readout: TES I-V



Simultaneously acquired I-V curves of three γ-ray TESs

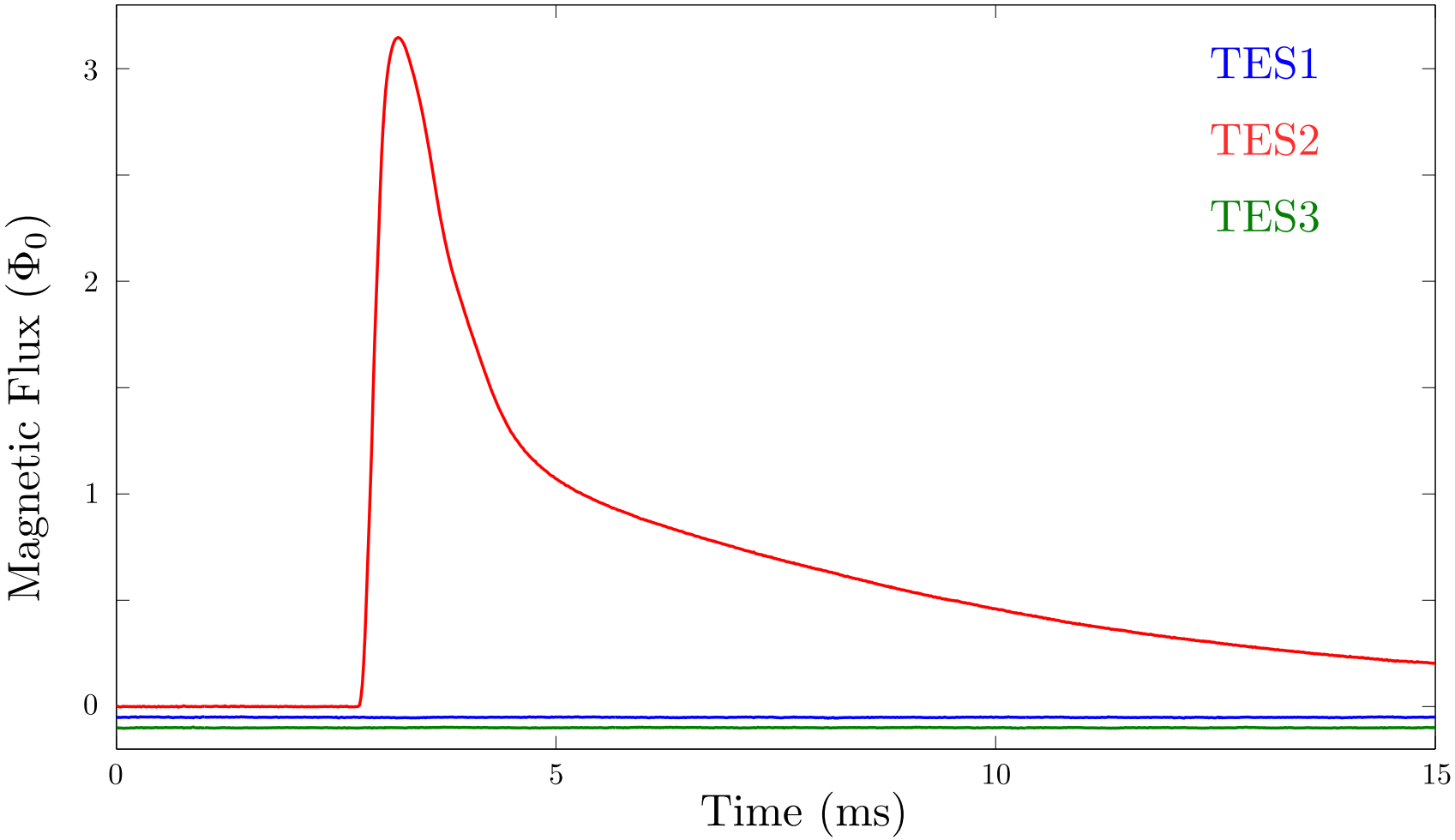
ROACH-2 readout: TES noise



TES noise far exceeds readout noise floor

Roach-2 readout: γ-ray pulses

Pulse in one of the simultaneously measured detectors



Pulse does not crosstalk into other detector channels

Conclusion

Demonstrated multiplexed readout of microwave SQUID multiplexers using ROACH-2 platform:

- Low readout noise
- Low crosstalk
- Scalable readout electronics

Future work:

- High-bandwidth μmux pixels
- Finish and debug readout firmware
- 256 pixel γ-ray spectrometer (SLEDGEHAMMER)
- Kilopixel neutrino mass experiment (HOLMES)
- And more!