Multiplexing Readout for Large format TES & MKID arrays

Zeesh Ahmed
SLAC National Accelerator Laboratory

October 9, 2016

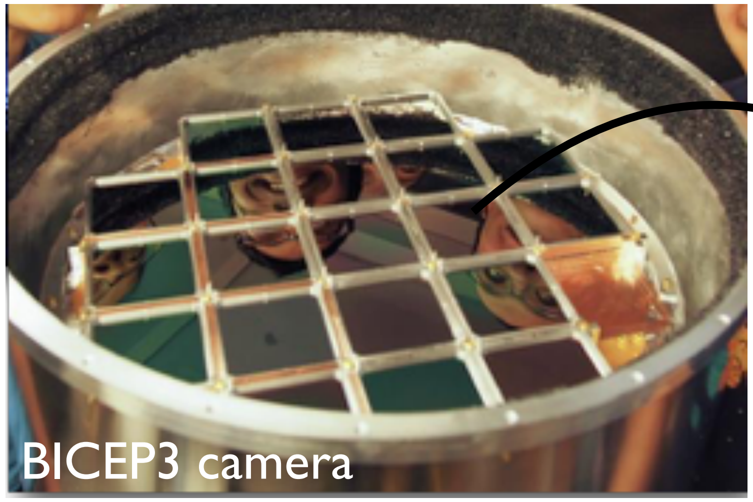
CPAD Instrumentation Frontier Meeting 2016:New Technologies for Discovery II

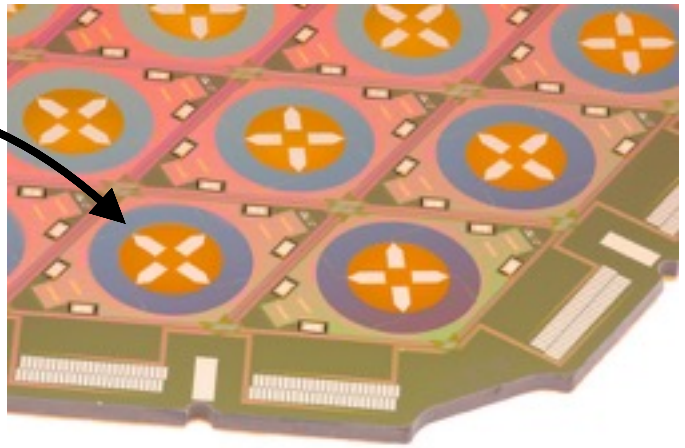
Outline

- Multiplexing of superconducting sensors: basics and taxonomy
- Traditional multiplexing for TES
  - DC-SQUID serial switching (Time Divison)
  - Series RF resonators (Frequency Division)
- MKID multiplexing
- Combining the best of TES and MKIDs
  - RF-SQUID coupled microwave resonators for TES multiplexing
- Warm Readout electronics for microwave resonators
  - FPGA+ADC/DAC for multi-channel homodyne readout
  - Current and upcoming systems
  - Tone tracking

Multiplexing basics

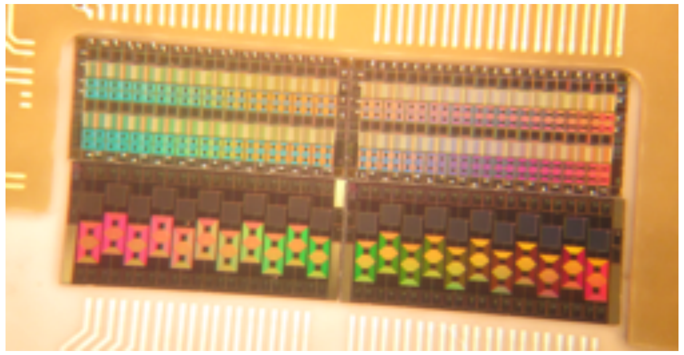
- Share sensor bias and signal wiring across many sensors of the instrument
  - Superconducting sensors are typically operated at subkelvin temperatures. So minimize heat load from room temperature
    - 100-300mK for imaging cameras (CMB, mm, sub-mm etc)
    - 50-100mK for solid-state particle detectors
  - Reduce system complexity and reduce integration burden
- Signals are multiplexed at or close to the temperature stage that houses the sensors.
- **MUX factor** = number of sensor signals carried per unit set of wires to room temperature





AdvACT sensors

+

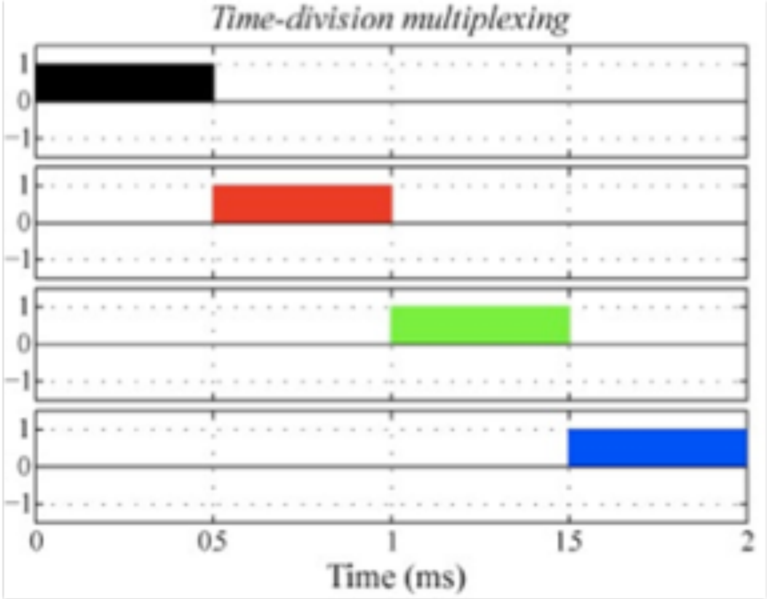


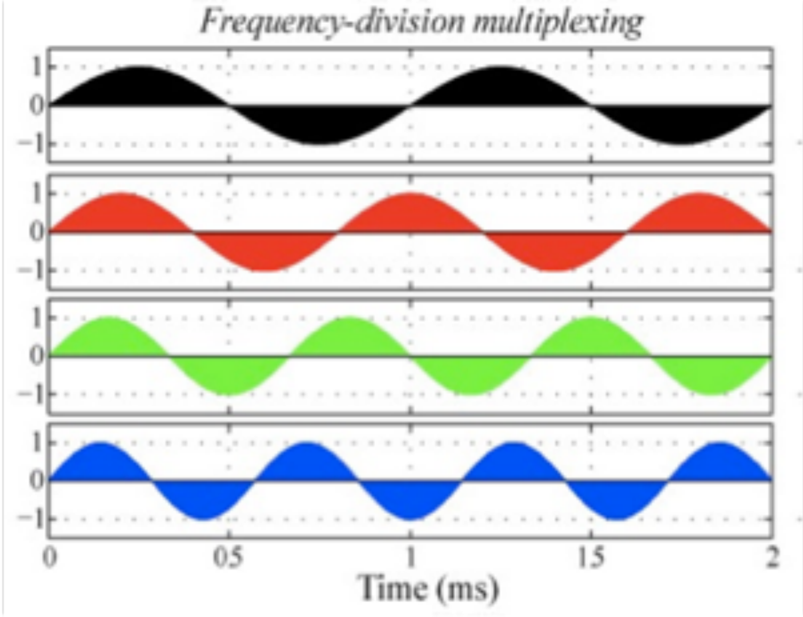
SQUID multiplexer

Multiplexer types

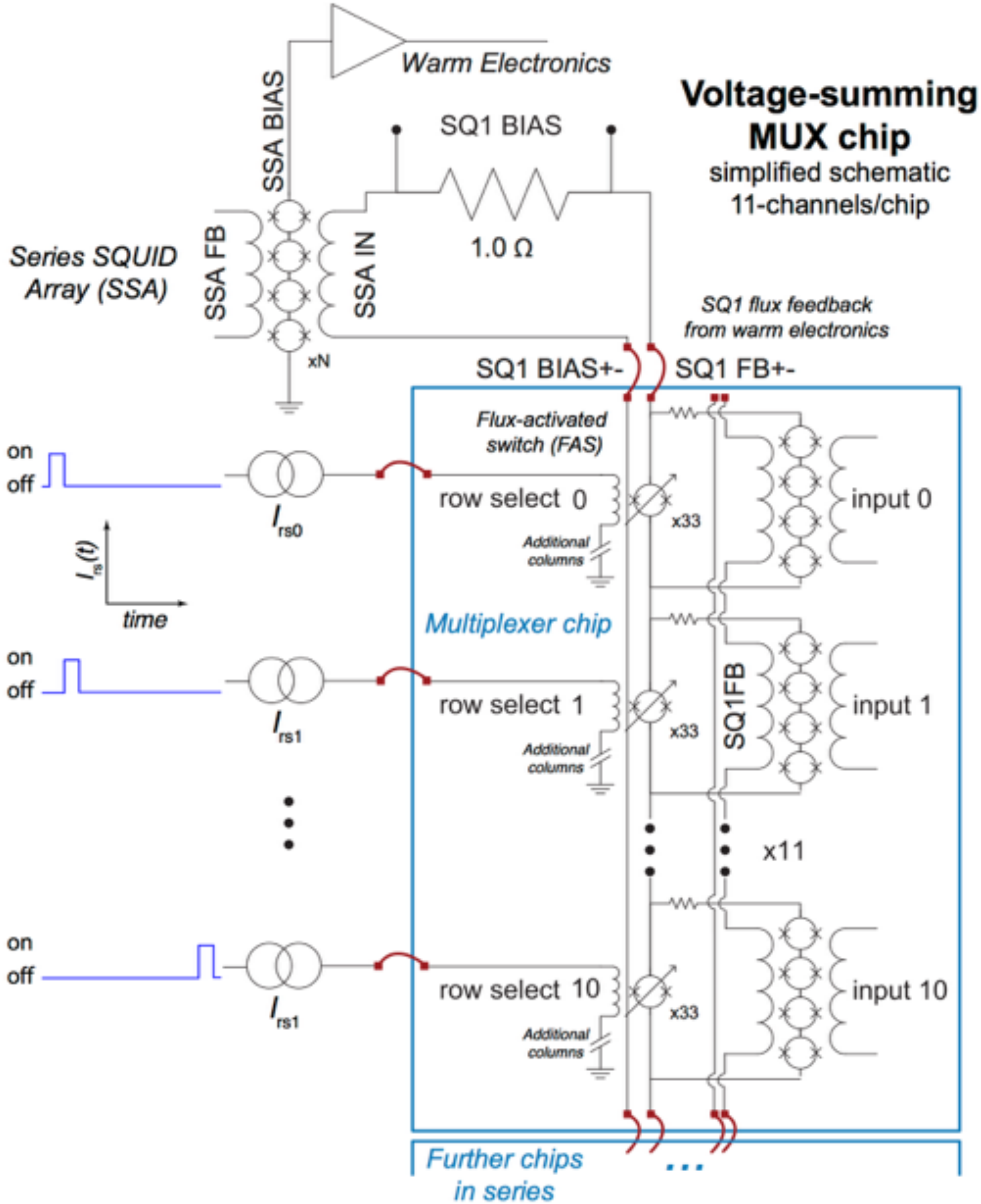
- Time division and frequency division MUX are common in CMB cameras

MUX basis/ Frequency regime	~RF O(1-100) MHz	~Microwave O(300MHz)+
Time-division	1. DC-SQUIDs used as switches to cycle through TESes (aka TDM)	--
Frequency-division	1. LC resonators in series with TESes (aka dfMUX) 2. MKIDs	1. LC resonators inductively coupled to TESes (aka microwave MUX) 2. MKIDs



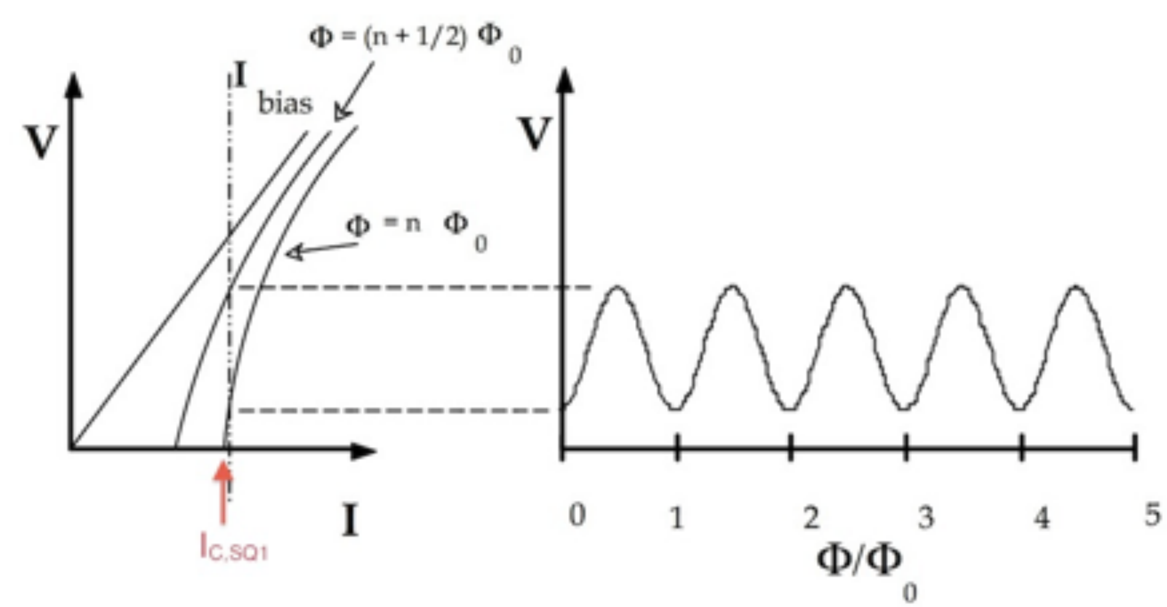


DC-SQUID serial switching of TES bolos (1)

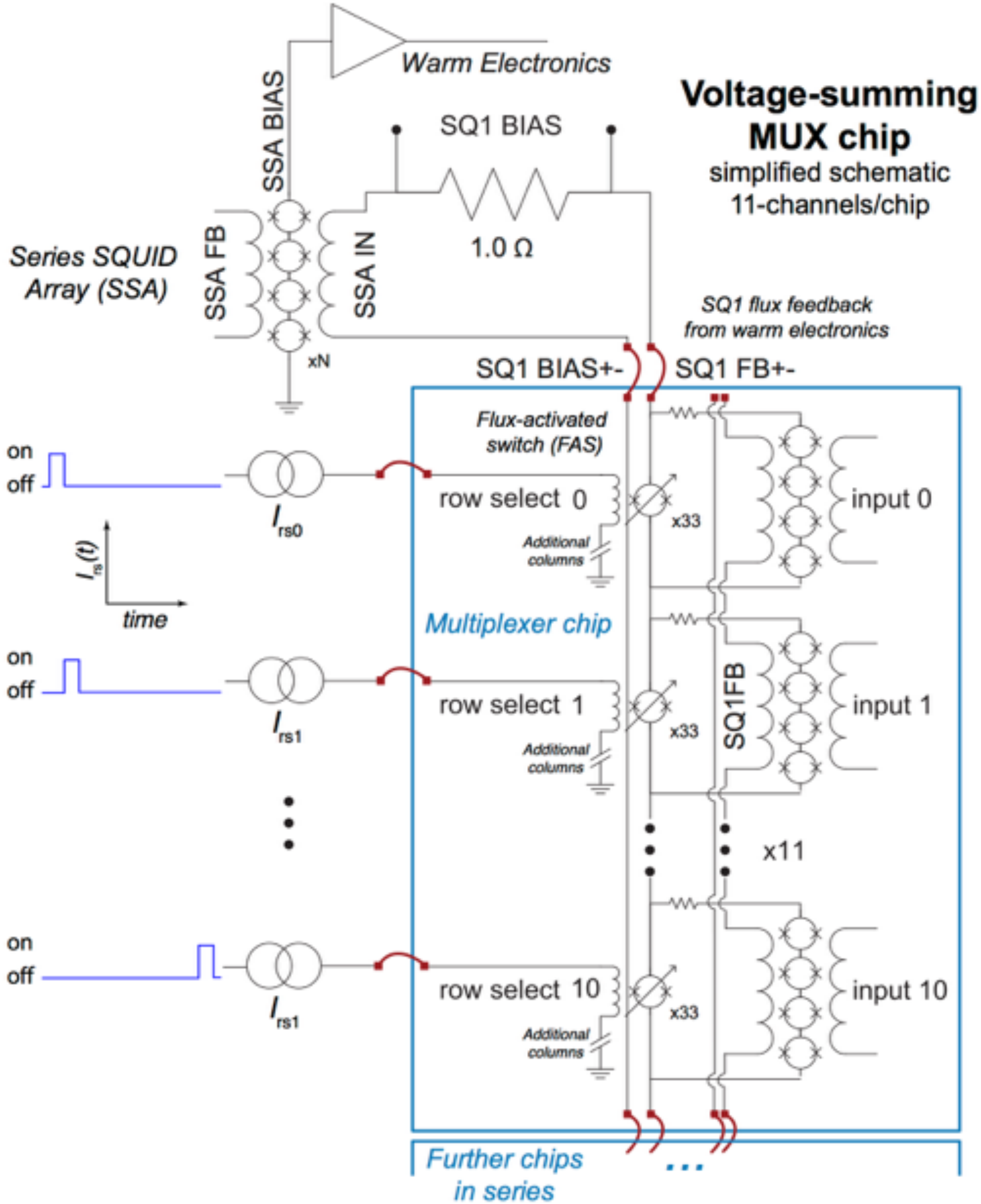


- TES bolo connected to inputs. Inputs amplified by SQUIDs
- 64 bolos per "column". Switch between "rows" serially.
- All columns read out at once, but only one row at a time.
- Active feedback linearizes SQUID response

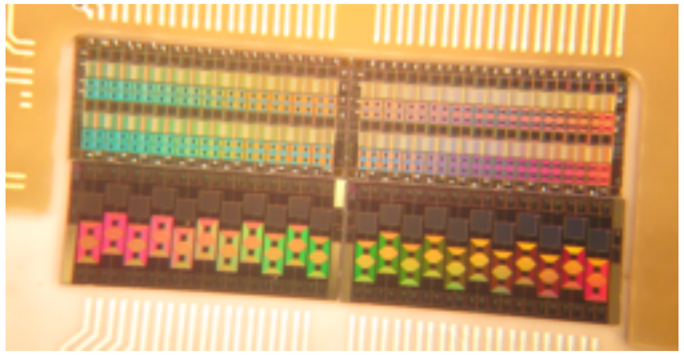
Rev. Sci. Instrum. 74, 3807 (2003)



DC-SQUID serial switching of TES bolos (2)

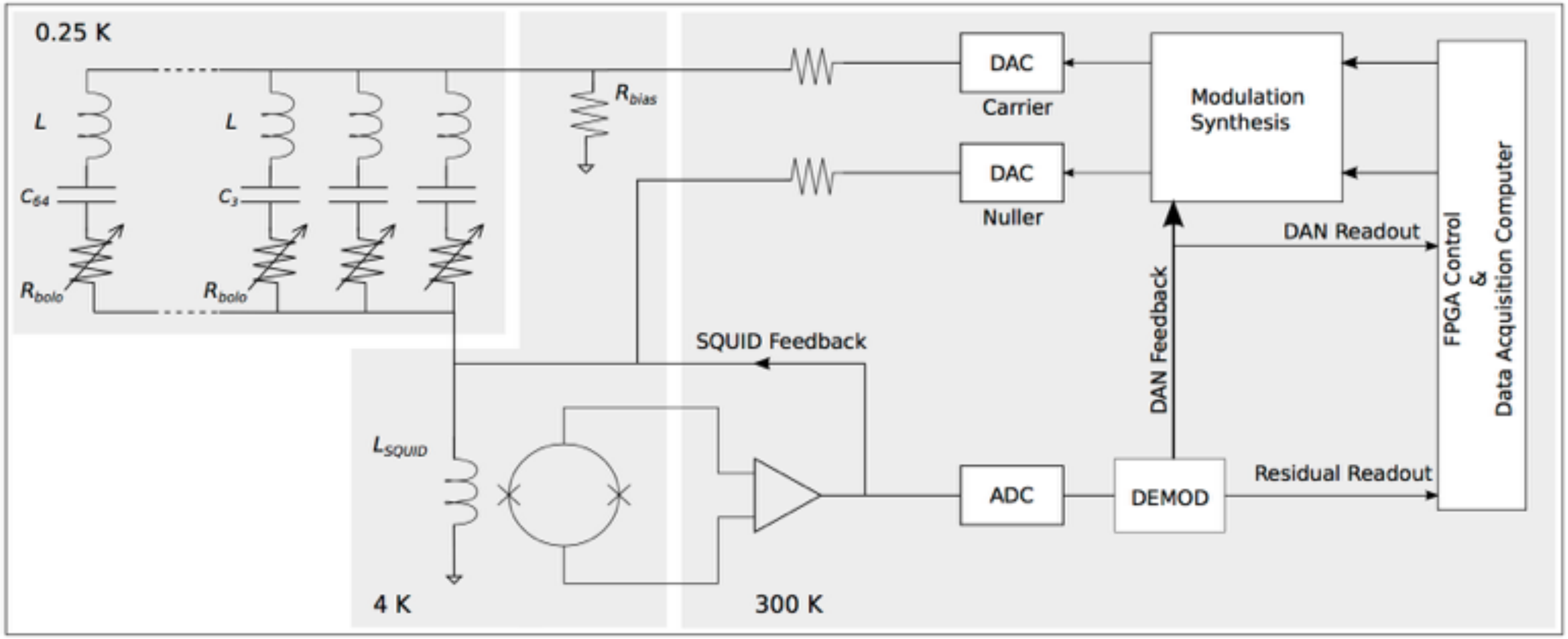


- MUX factor set by SQUID bandwidth divided by TES bandwidth
  - Today: 64
  - With R&D effort: 128-256
- R&D effort
  - Bandwidth adjustments



SQUID multiplexer chip

RF resonators in series with TES bolos (1)

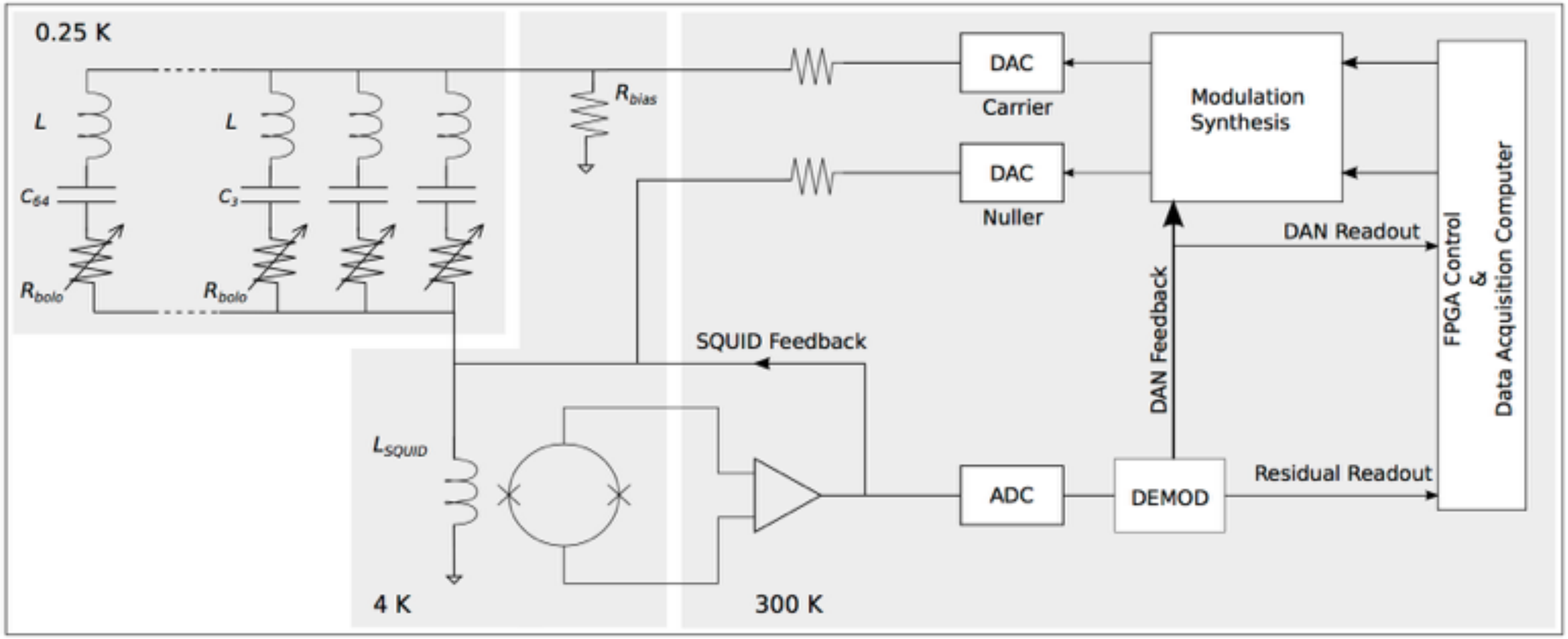


- TES bolos are dissipative elements in ~MHz resonators at unique frequencies in parallel
- 64 bolos on one frequency comb, amplified by single SQUID.
- Active feedback linearizes SQUID response

dfMUX LC board

Rev. Sci. Instrum. 83, 073113 (2012)

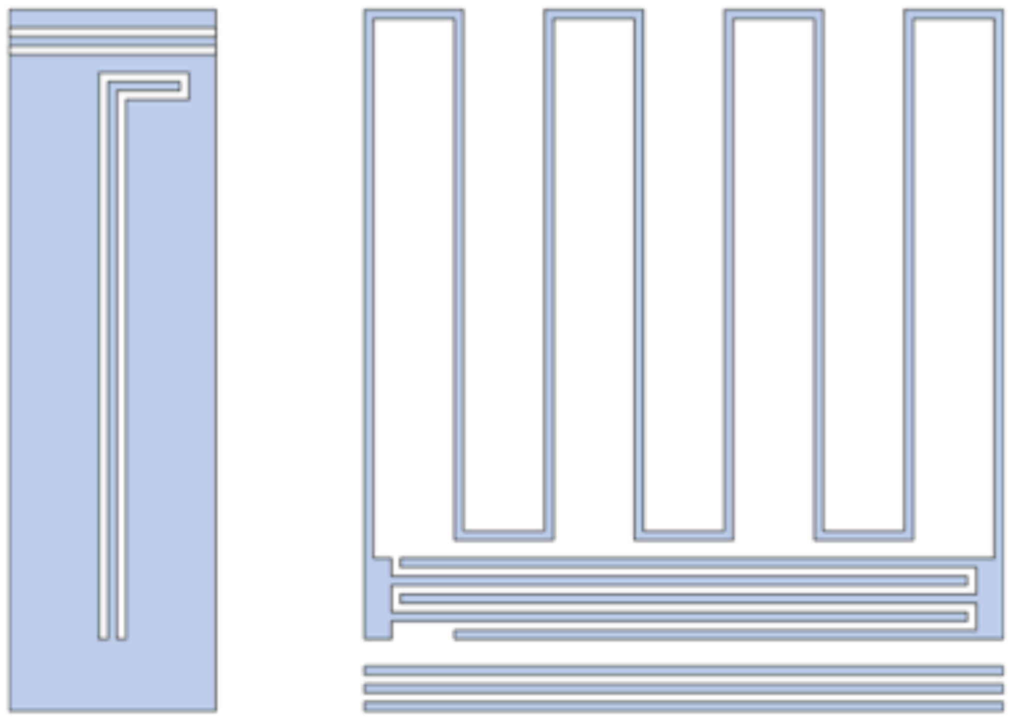
RF resonators in series with TES bolos (2)

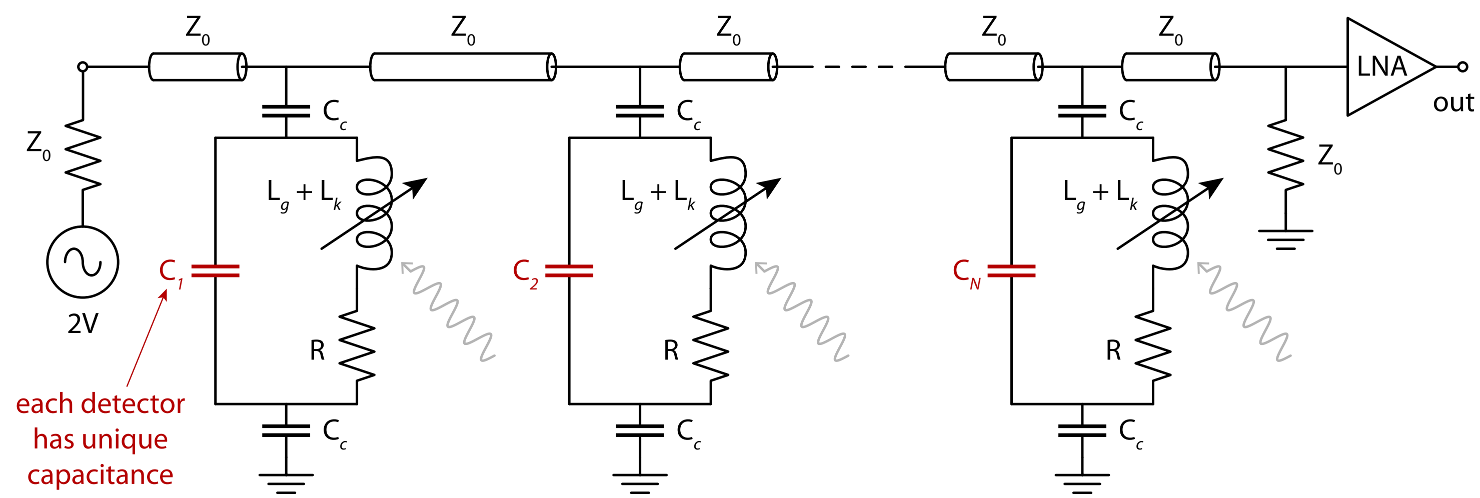


- MUX factor set by electronics bandwidth and resonator spacing
  - Today: 64
  - With R&D effort: 128-256
- R&D effort
  - Stray inductance control
  - Increase ADC/DAC bandwidth

dfMUX LC board

MKID cold multiplexing (1)

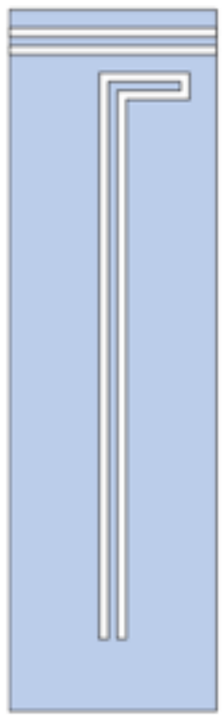


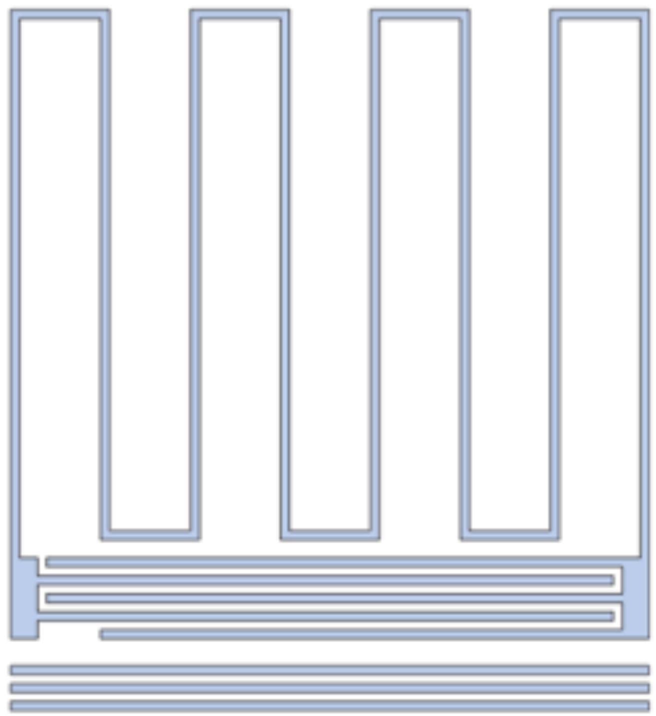


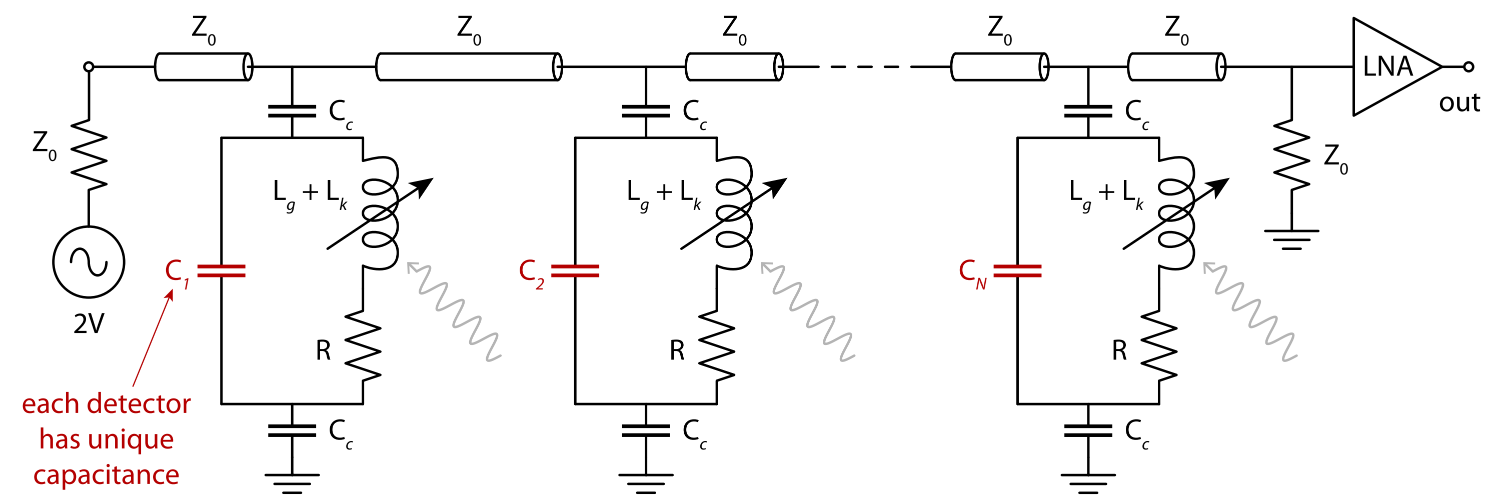
- O(100-1000) MHz resonators. Inductor is sensor
- Capacitively couple to a feedline
- Cold amplification by LNA at ~few K

Annu. Rev. Condens. Matter Phys. 2012. 3:169–214

MKID cold multiplexing (2)

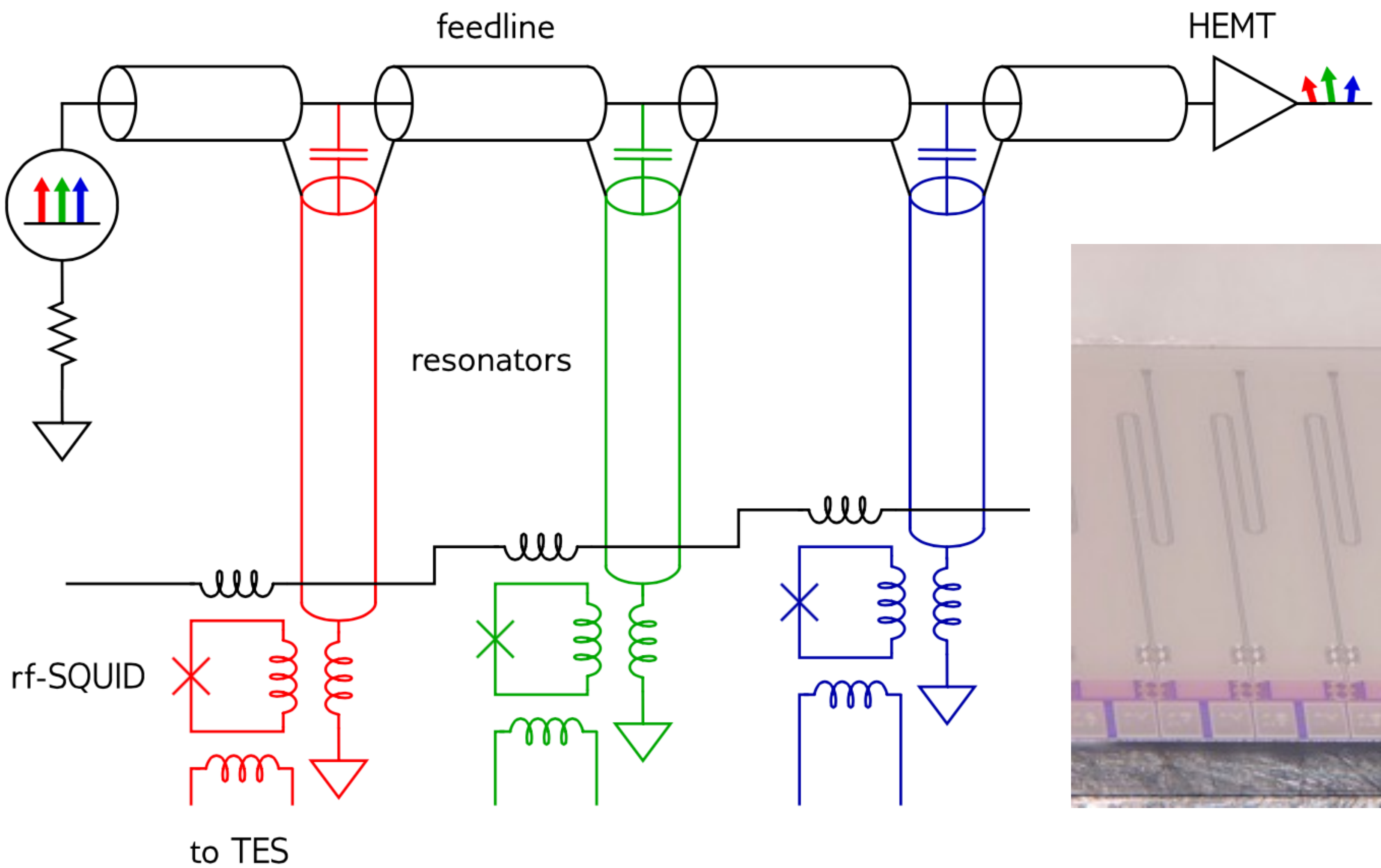


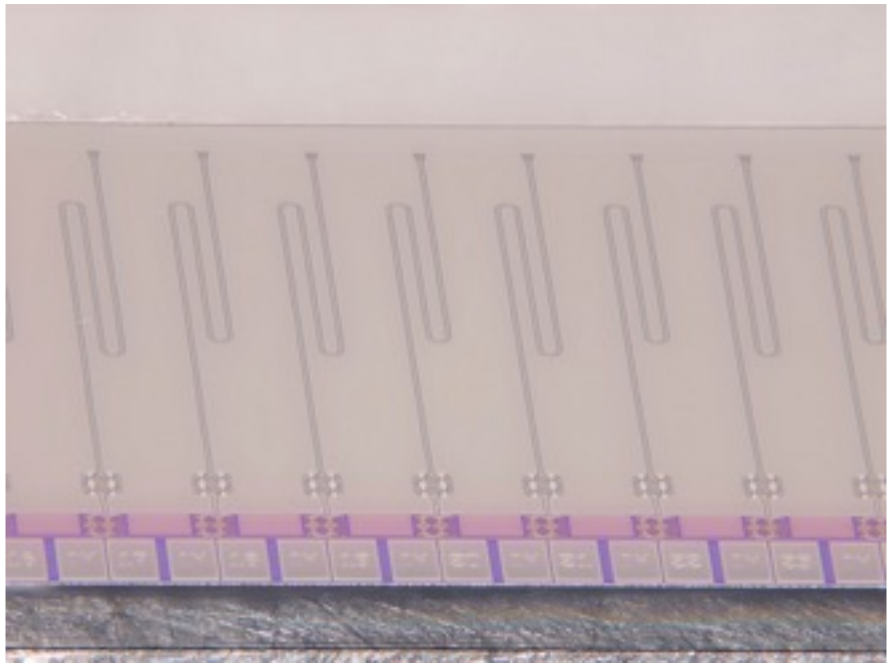




- MUX factor set by electronics bandwidth and resonator spacing
  - Today: 256-500
  - With R&D effort: 1000+
- R&D effort
  - System noise depending on application (eg. CMB 150GHz NEPs, 0.1-1Hz)
  - Resonators — materials, Qs, packing

Microwave resonators to multiplex TES bolos (1)

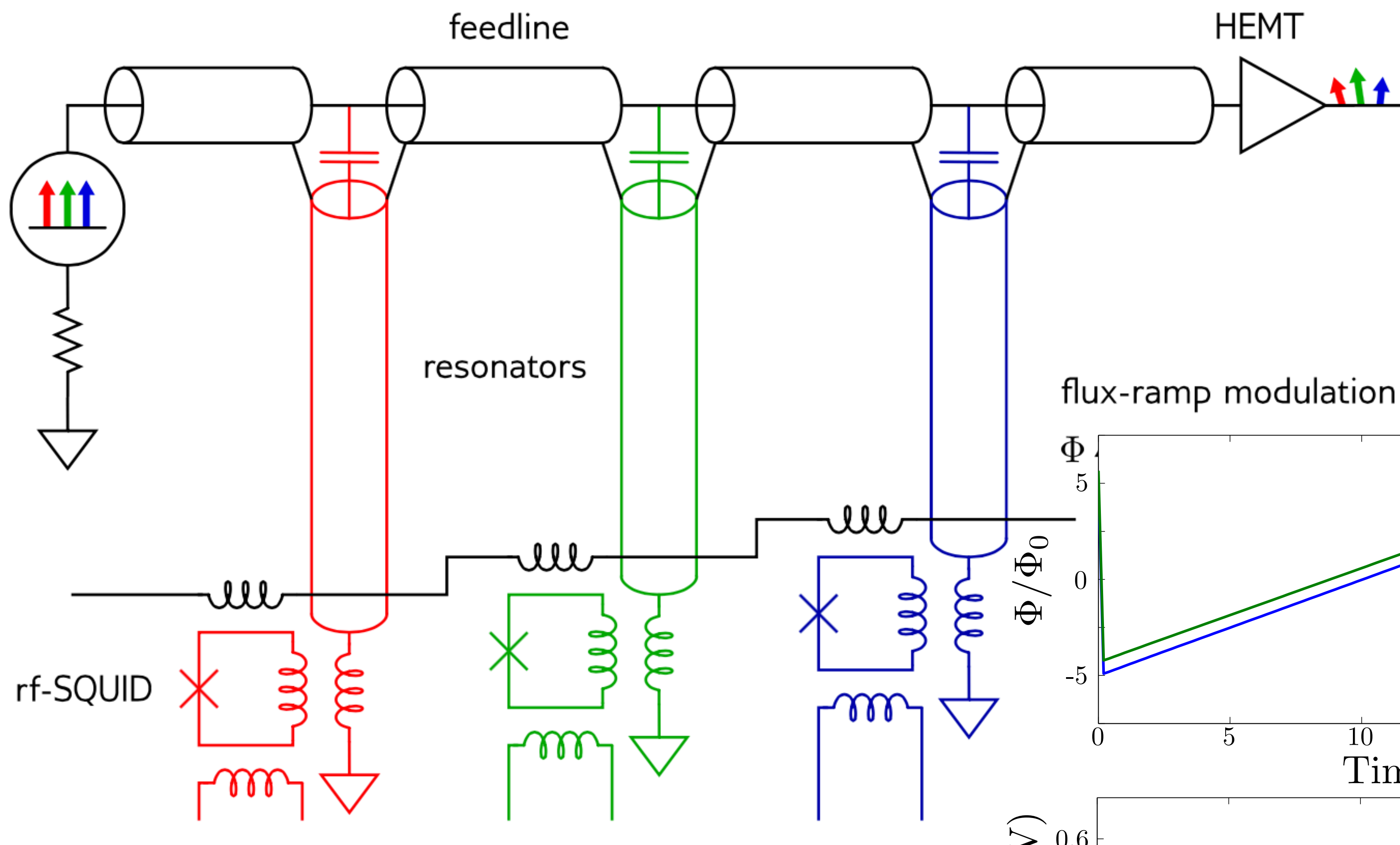


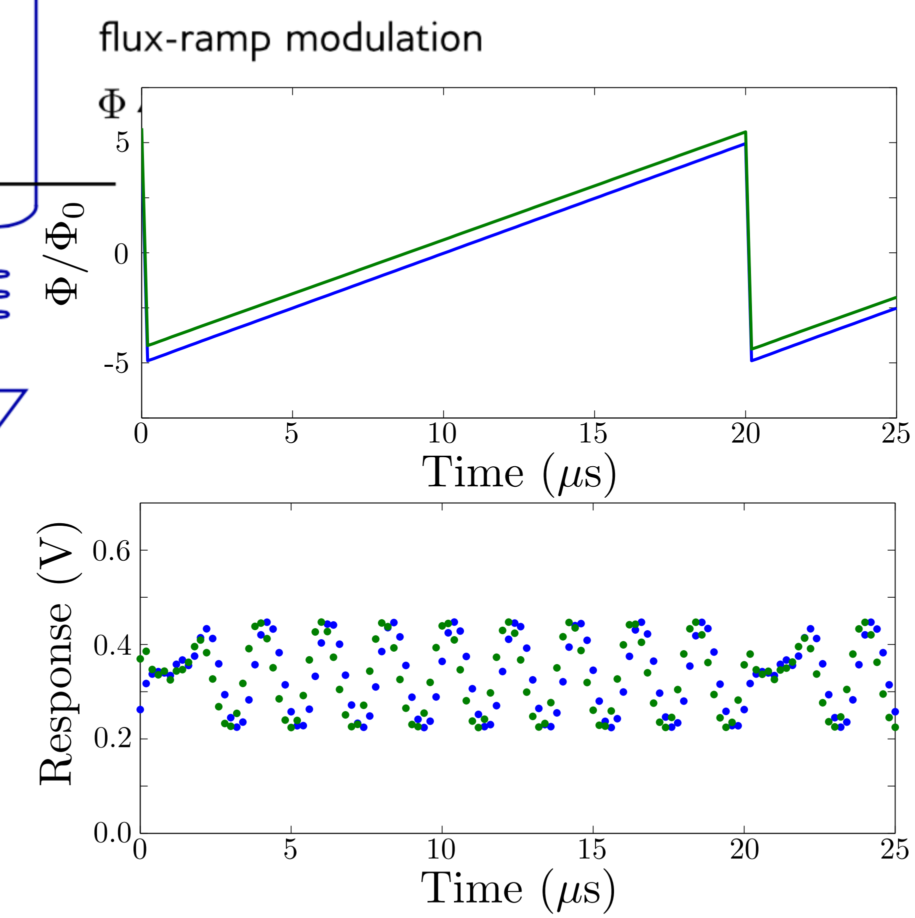


- Combine the immense multiplexability of microwave resonators with the heritage and maturity of TES and SQUIDs
- TES inductively couples to RF-SQUID, which screens a GHz resonator
- Signal in TES changes inductance, hence frequency of resonance. No change in Q

Appl. Phys. Lett. 85, 2107 (2004)

Microwave resonators to multiplex TES bolos (2)

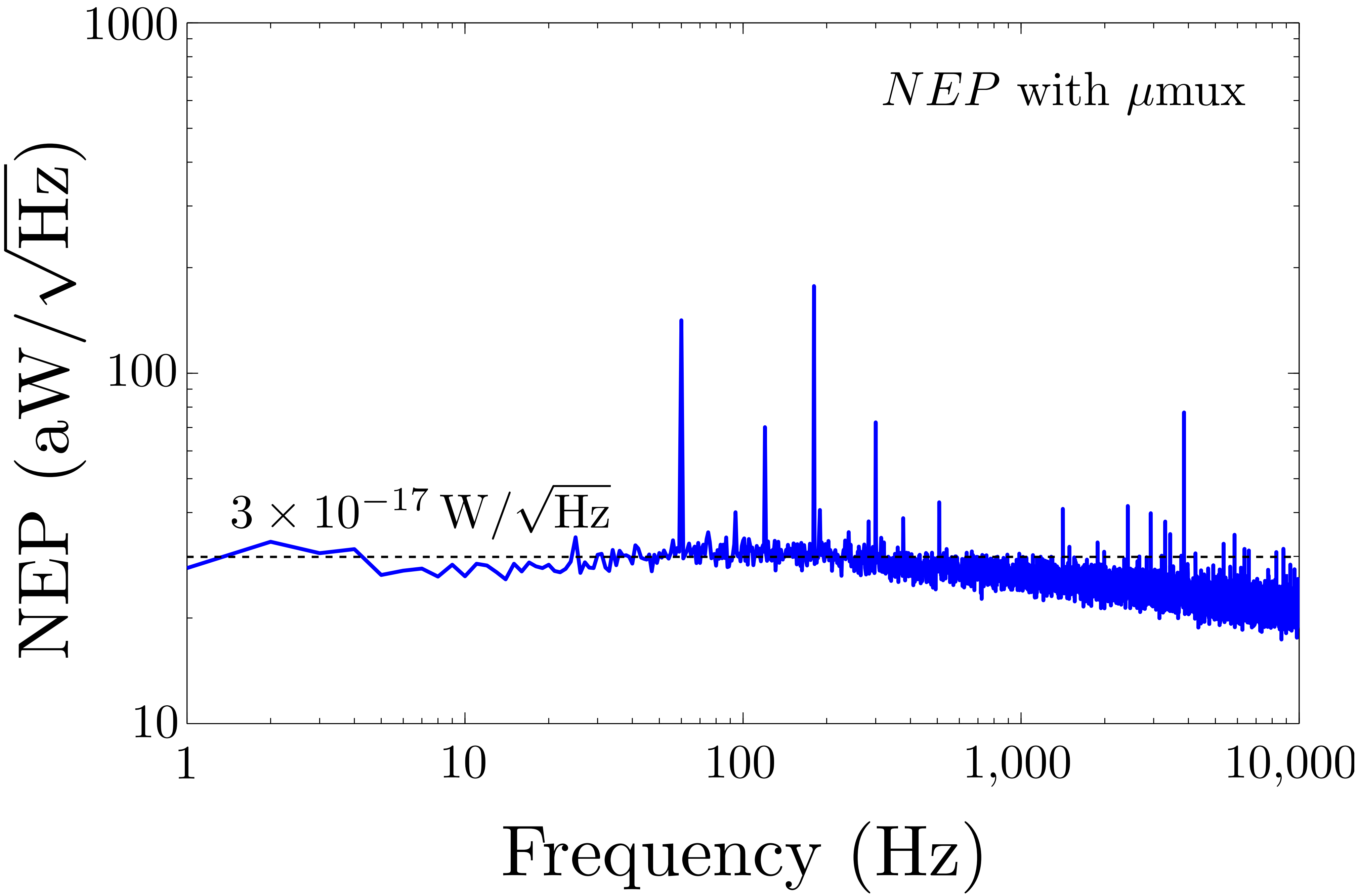




- Flux modulation linearizes SQUID response
- Also enables bypassing of TLS noise in resonator capacitor

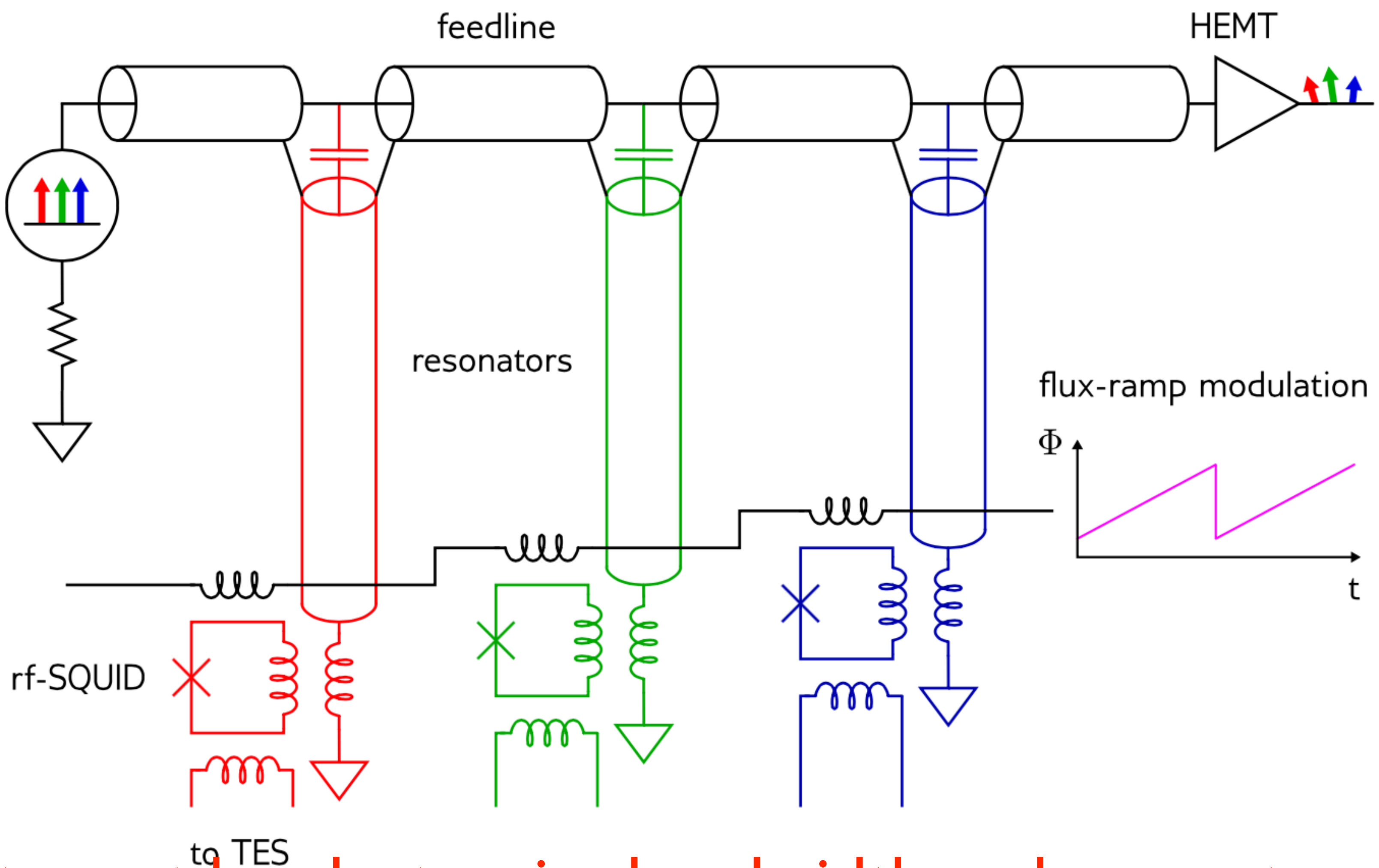
B. Mates dissertation (2011)

Linearize response, mitigate low-frequency TLS



B. Mates dissertation (2011)

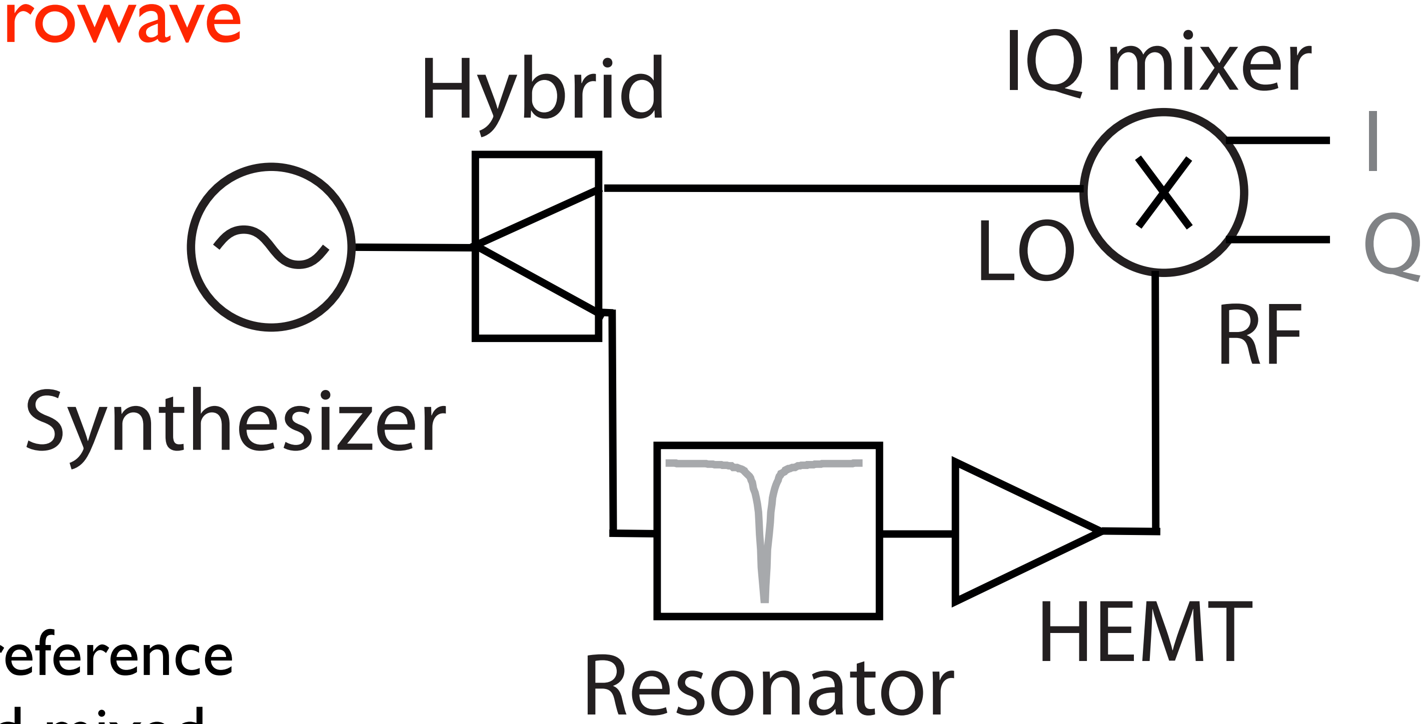
Microwave resonators to multiplex TES bolos (3)



- MUX factor set by electronics bandwidth and resonator spacing
  - Today: 64 demonstrated; 256-500 (MKID)
  - With R&D effort: 1000+
- R&D effort
  - Resonator packing
  - Integration with TES
  - Readout electronics

Warm readout electronics for microwave schemes

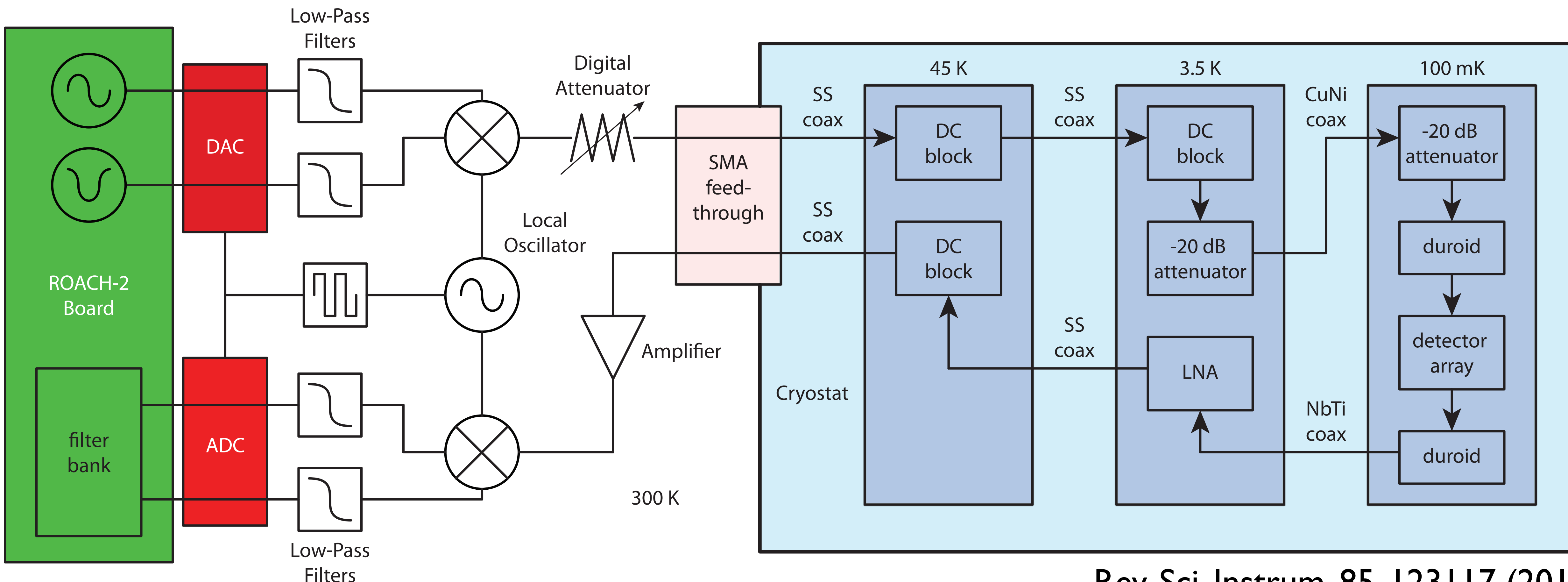
- Warm (300 K) electronics synthesize input microwave tones to drive the resonators and to channelize and demodulate the output microwave tones
  - ADC, DACs
  - FPGAs



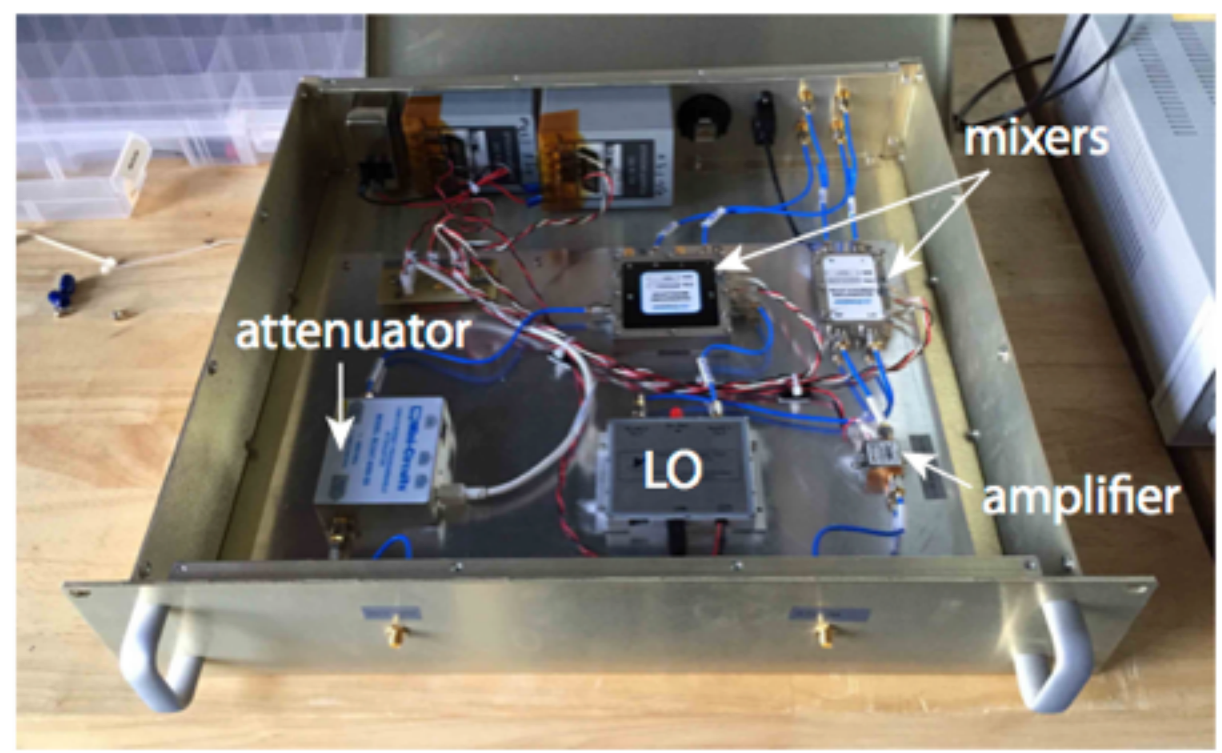
- Homodyne scheme
  - Synthesized signal split into a reference arm and measurement arm and mixed after measurement

- ADCs and DACs operate in a baseband (~MHz) and are up-/down-mixed for signal band

ROACH-2 (256-512 channels)



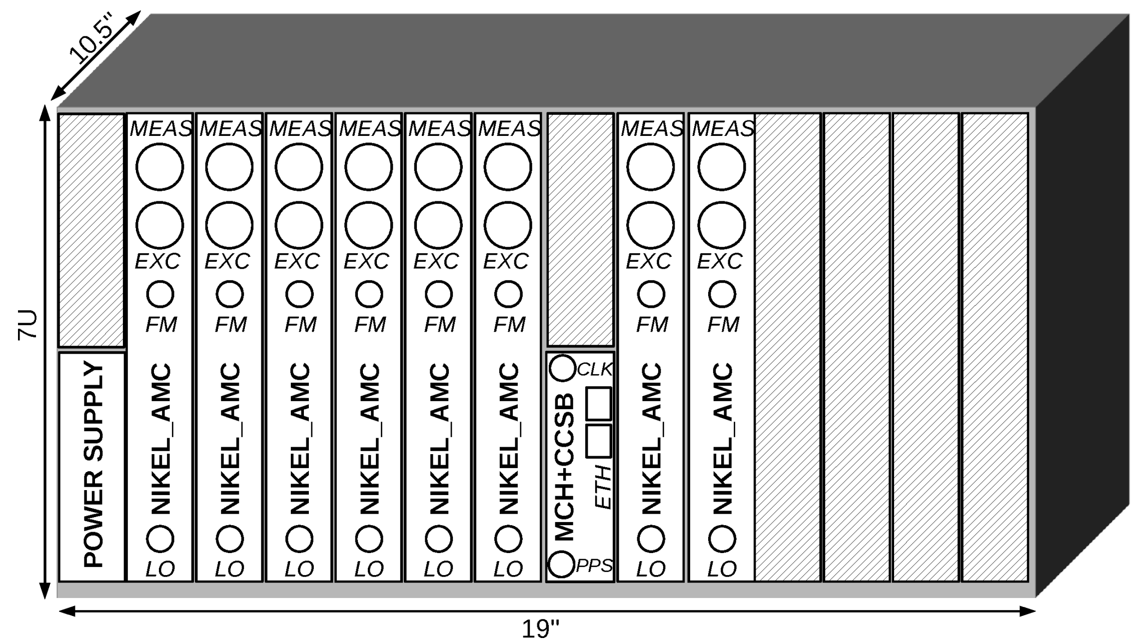
Rev. Sci. Instrum. 85, 123117 (2014)



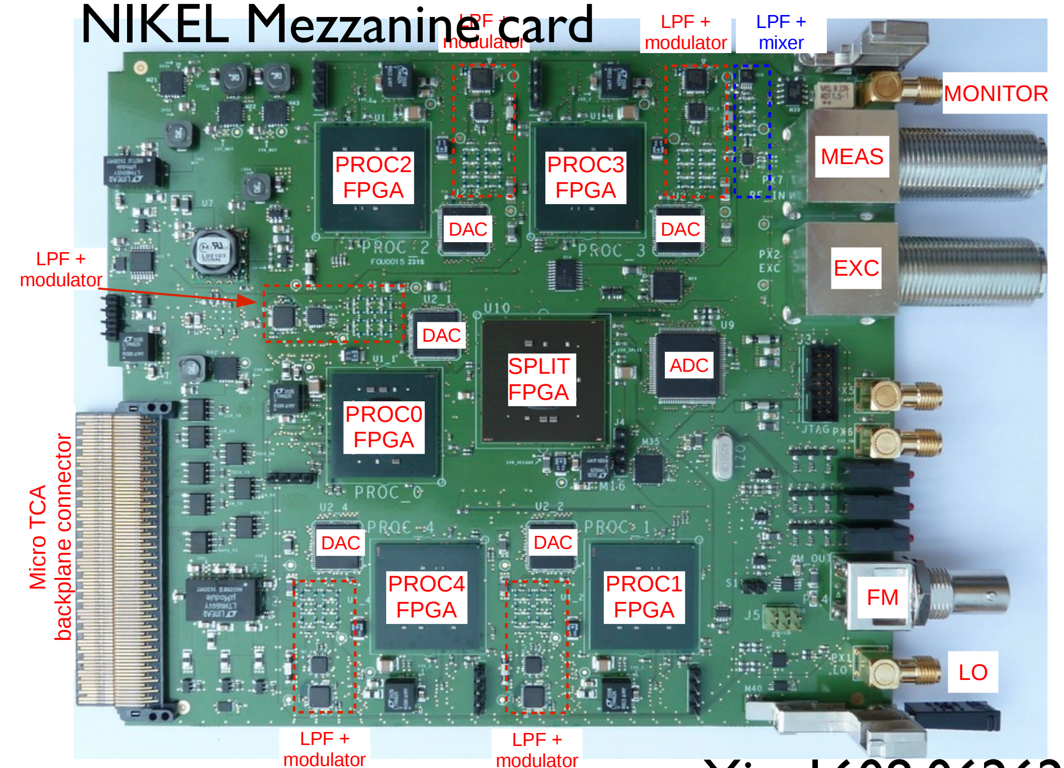
NIKA system (NIKEL ~256), McGill system (ICE ~128)

arXiv: 1602.01288

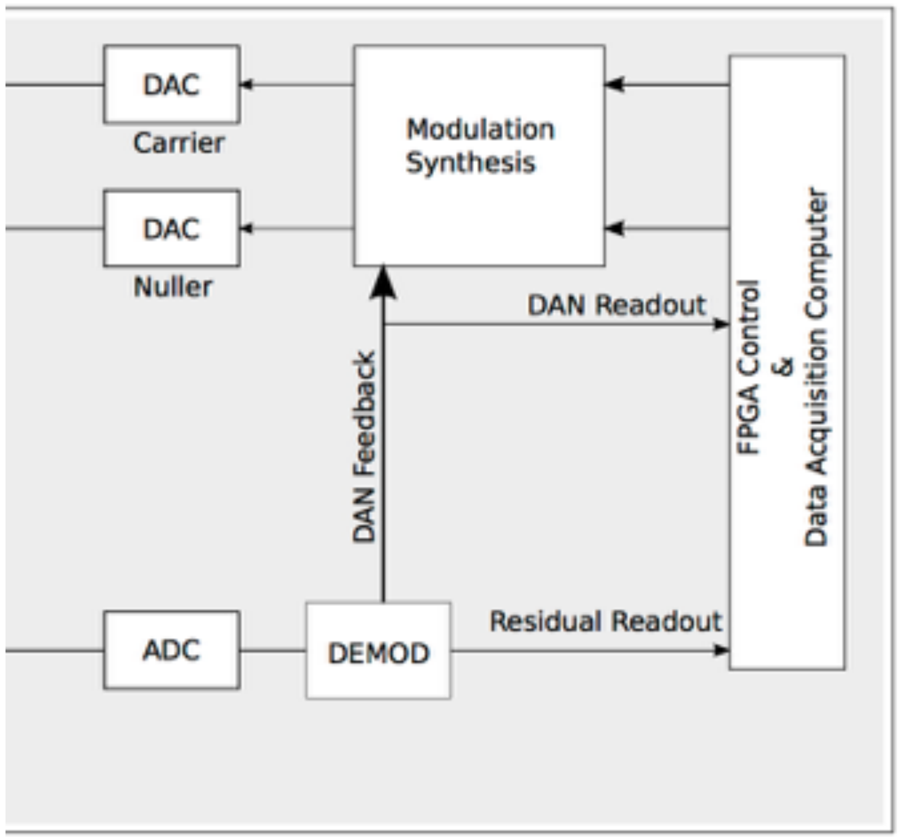
NIKEL Crate



NIKEL Mezzanine card

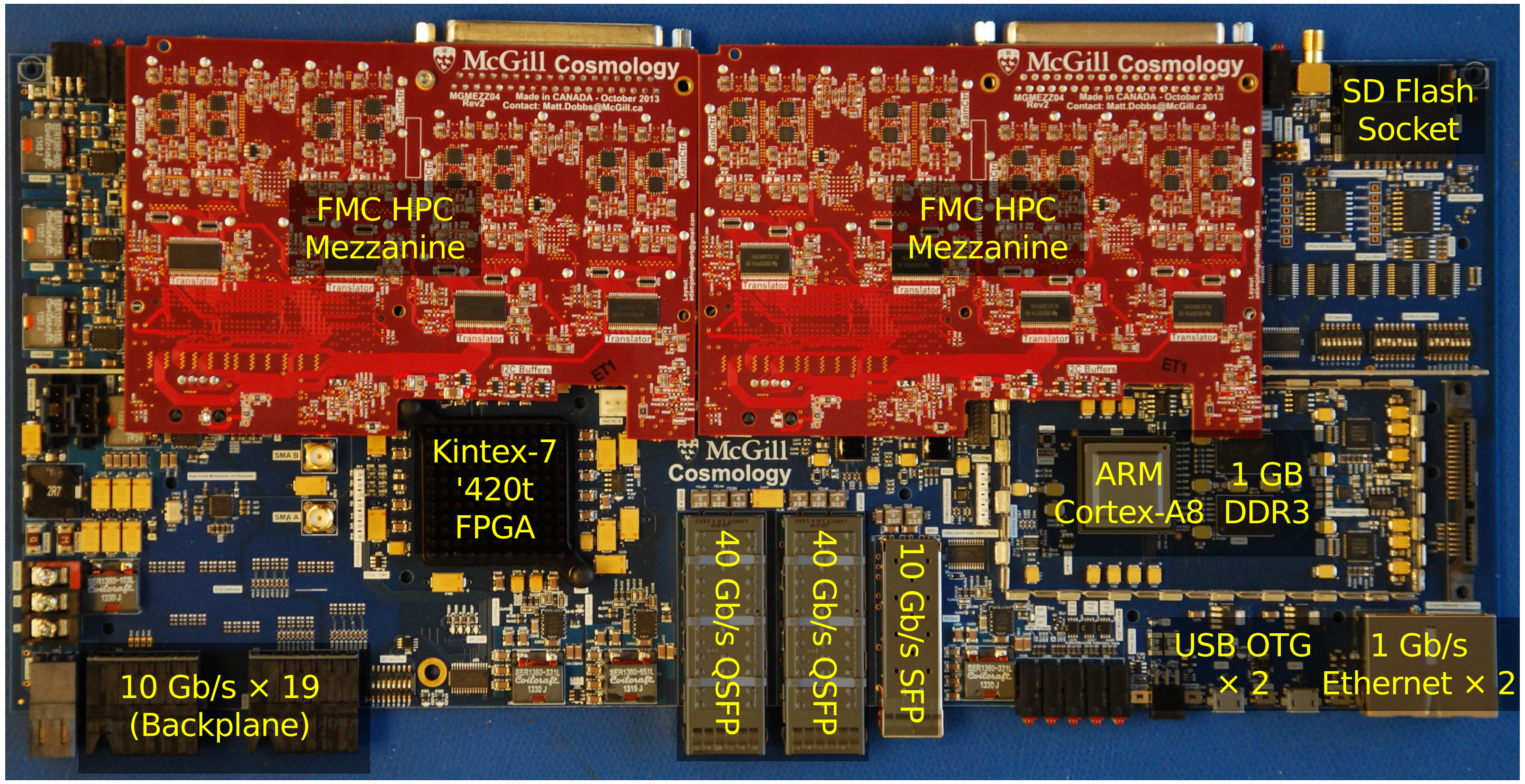


ICE schematic

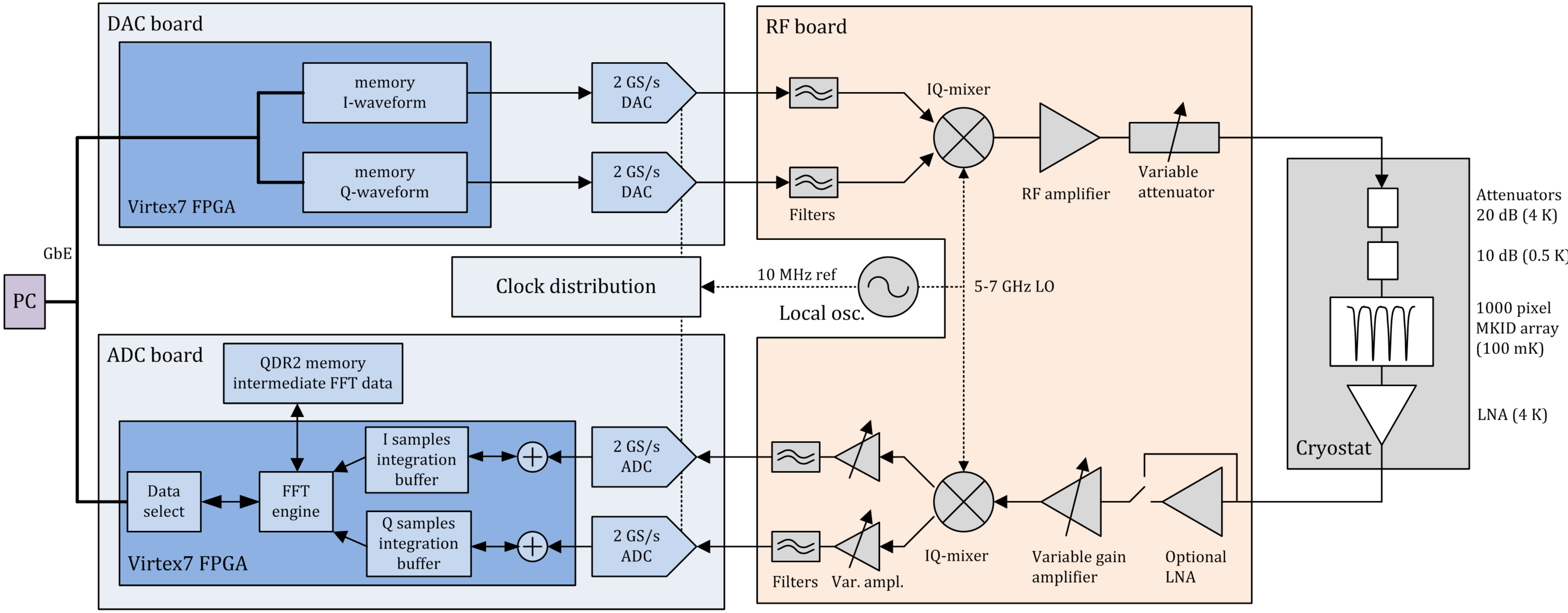


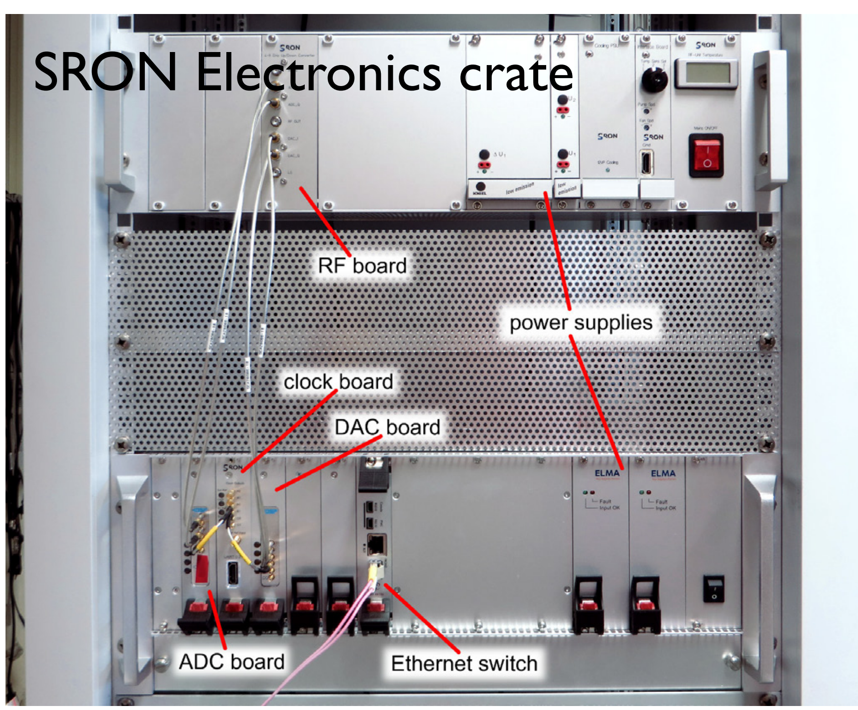
ICE hardware

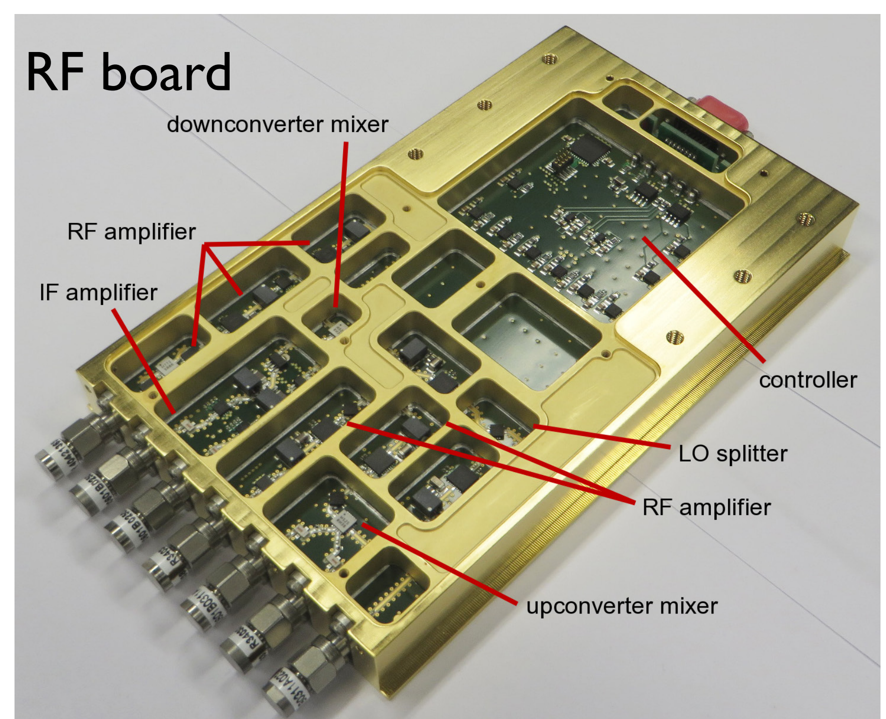
arXiv: 1608.06262



SRON system (~1000 channels)







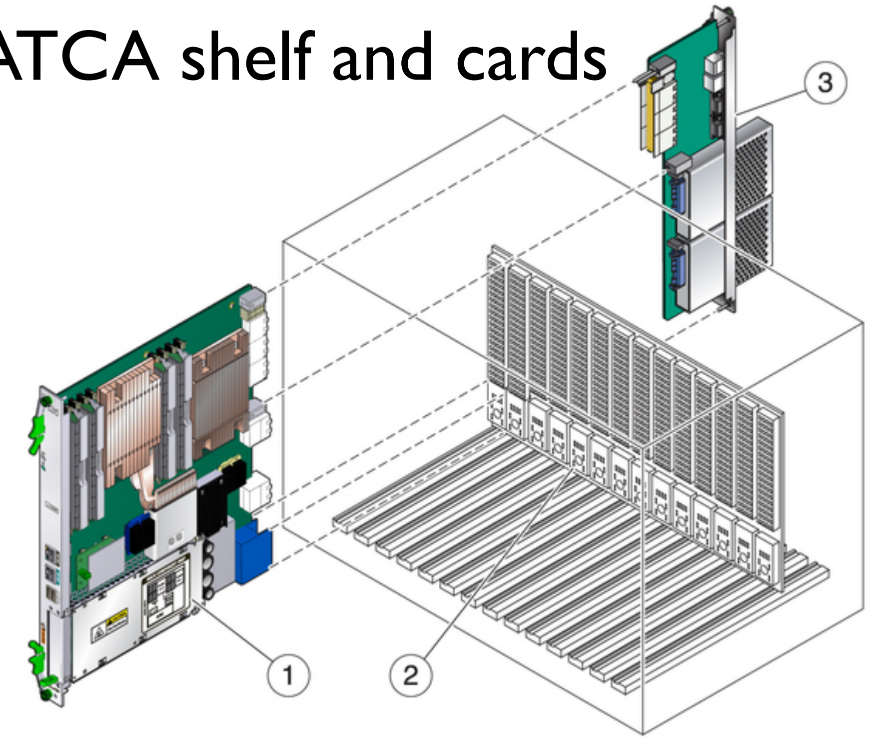
arXiv: 1507.04151

SLAC: tone-tracking readout (1000+)

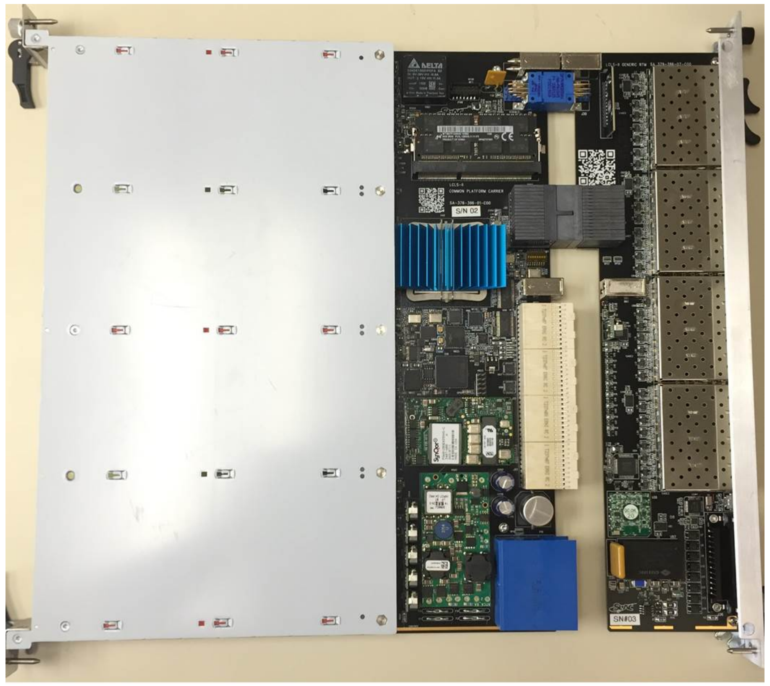
- Frequency of probe tones is actively adjusted to track resonance.
- Enables packing more resonances in a given RF power budget.
- Direct digital synthesis and demod (no IQ)
- Being built for LCLS-II based on existing ATCA heritage at SLAC for particle physics and RF engineering in LCLS-I.
- A carrier card provides
  - 4GHz bandwidth
  - Upto 4000 channels
- Electronics / RF design nearing completion, full hardware prototype in late 2016.
- Plans to make this general purpose and serve TES/MKID applications

J. Frisch, S. Smith, D. Van Winkle, R. Herbst, TID-AIR

ATCA shelf and cards



Carrier cards



Warm readout R&D effort

- Higher bandwidth ADC/DACs without sacrificing readout noise
- Take advantage of increasing FPGA capacity
- Low-frequency noise control — monitoring tones to characterize correlated electronic noise
- System linearity (end-to-end)
- Common development for microwave-interrogated techniques

Conclusions

- Traditional MUXing in TES
  - MUX ~64
  - With appropriate R&D, expect to go to 128-256
  - Will serve our short-term instrumentation needs (~2-3 years)
- Microwave resonators
  - MUX ~256
  - With appropriate R&D expect to go to ~1000, likely 1000++
  - TES MUXing on equal footing with MKIDs with GHz resonator-coupled schemes
  - Will serve our medium-term (5+ years) and longer instrumentation needs
- Warm readout
  - ADC, DAC and FPGA technology advancing quickly
  - With appropriate R&D can capitalize and make high-density readout systems
- Ideas for MUX ~O(10,000) are being considered for 10+ yr needs