



**HAL**  
open science

# MULTIPLEXAGES de Signaux Analogiques - Applications Cryogéniques

Damien Prêle

► **To cite this version:**

Damien Prêle. MULTIPLEXAGES de Signaux Analogiques - Applications Cryogéniques. École thématique. France. 2018. hal-03767840

**HAL Id: hal-03767840**

**<https://cel.hal.science/hal-03767840>**

Submitted on 2 Sep 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# MULTIPLÉXAGES de Signaux Analogiques

Applications **CRYOGÉNIQUES**

DÉTECTION DE RAYONNEMENT  
À TRÈS BASSE TEMPÉRATURE



- ▶ *SQUID multiplexers for TES* - K. D. Irwin - Physica C 2002
- ▶ *Shannon Limits for LowTemperature Detector Readout* - K. D. Irwin - 2009
- ▶ *Dev. of FDM for the X-IFU* - H. Akamatsu et al. - 2016
- ▶ *SQUID readout multiplexers for TES arrays* - A.T. Lee - NIMA2006
- ▶ *High-resolution  $\gamma$ -ray spectroscopy with a microwave-multiplexed TES array* - O. Noroozian et al. - 2013
- ▶ *Readout of two-kilopixel TES arrays for Advanced ACTPol* - S.W. Henderson
- ▶ *Le bolomètre résistif* - L. Rodriguez - DRTBT2009
- ▶ *SQUID et Multiplexage* - D. Prêle - DRTBT2009
- ▶ *Front-end Multiplexing* - D. Prêle - INFIERI2014
- ▶ *Front-end multiplexing—applied to SQUID multiplexing* - D. Prêle - JLTP2015
- ▶ *Supercon. mux for arrays of TESs* - JA. Chervenak - APL1999
- ▶ ...

## Plan :

Basic multiplexing

Mux/Demux of *tones*

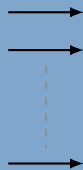
Techno. review

# Multiplexing general

Transmission of N signals over 1 channel

INFORMATION

N data/signals



Multiplexer

TRANSMISSION

One channel



Introduced for telegraphy at the end of the 19<sup>th</sup> century and widely applied in **telecommunications** during the 20<sup>th</sup> century :

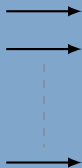
*several telephone calls may be carried using one wire*

# Multiplexing general

Transmission of  $N$  signals over 1 channel

INFORMATION

$N$  data/signals



Multiplexer

TRANSMISSION

One channel



*That is **not a real multiplexer**, because this need to reduces - **Data compression** - the transmitted informations to use the **same output channel capacity***

# Multiplexing general

Transmission of  $N$  signals over 1 channel with HIGHER "capacity"

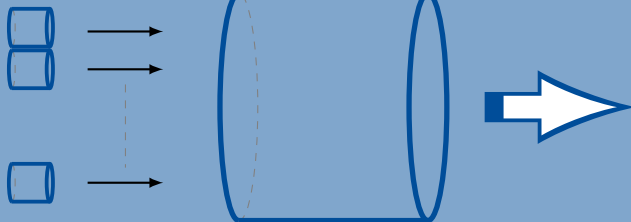
INFORMATION

TRANSMISSION

$N$  data/signals

Multiplexer

One channel



**!** *To transmit  $N$  signals via One channel, **the "channel" must provides better performances** than for a single signal transmission.*

## Multiplexing notice



To transmit N signals *via* one channel, **the "channel" must provides better performances** than for a single signal transmission.

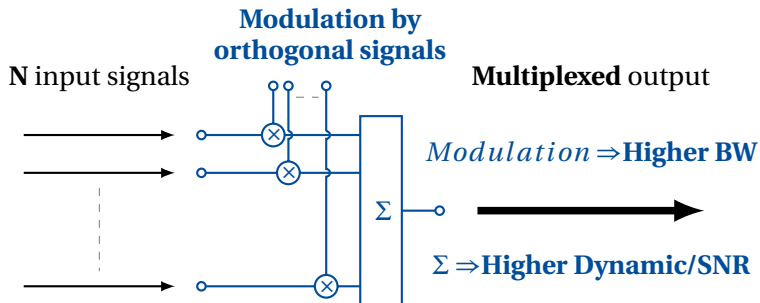
- ⇒ The increasing of the required performances is directly linked to the number N of multiplexed signals.
- ⇒ The affected performances are both :
  - ▶ Band Width
  - ▶ Dynamic / Signal to Noise Ratio

the multiplexing **divides the capacity of the high-level communication channel** into several **low-level sub-channels**, one for each message, signal or data to be transmitted.

## Multiplexing as a modulation

*There are intersections between modulation and multiplexing*

Multiplexing = modulation of input signals by orthogonal signals:

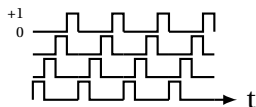


Orthogonal : **boxcar functions** or **carriers at different frequencies**.

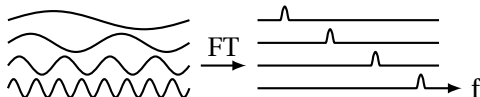
Orthogonality ⇒ demultiplexer **able to recover each input signal without interference from the other**.

# Orthogonal functions

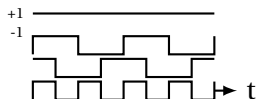
- ▶ boxcar functions  $\equiv$  **sampling**



- ▶ carriers  $\equiv$  **modulation**



- ▶ linear codes\*  $\equiv$  **coding**



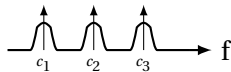
\* as used for error-detection/correction code. Especially, Hadamard/Walsh code could be used for multiplexing.



# limitations

Multiplexing  $\equiv$  **modulation/sampling/coding + summation**

- ▶ Frequency modulation  $\rightarrow$  cross-talk between two carriers / **bandwidth margin required**



- ▶ Nyquist–Shannon sampling<sup>†</sup> theorem  $\rightarrow$  aliasing<sup>‡</sup> / **noise margin required** and cross-talk



- ▶ Summation  $\rightarrow$  increasing of the amplitude range : **dynamic margin required**

$$\text{Wave 1} + \text{Wave 2} + M = \text{Summed Wave} \rightarrow t$$

The diagram shows three waveforms being summed together. The first is a sine wave, the second is a square wave, and the third is a complex waveform labeled  $M$ . The result is a complex waveform labeled 'Summed Wave' on a time axis  $t$ .

<sup>†</sup> A time domain multiplexer do not "see" the input signal all the time

<sup>‡</sup> High frequencies are mixed with low frequency / White noise increase

## Requirement for multiplexing

To multiplex a signal, the readout system (multiplexer) **must have better performances** than to read-out a single pixel.

*If the readout channel has performances better than what it is needed for the readout of a single pixel, a multiplexing can be performed **without signal degradations**.*

The multiplexer must have better :

- ▶ **bandwidth** ,
- ▶ **dynamic range** and/or
- ▶ **noise performances**.

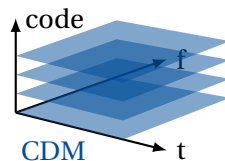
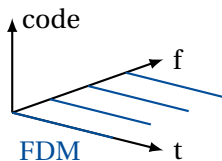
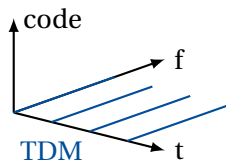
than for a readout of one pixel.

*The increasing of the needed performances for a  $N$  to 1 multiplexer must be better **by a factor of about  $\sqrt{N}$**  to few  $N$  ...*

# Multiplexing type *vs* standard modulations

- ▶ Multiplexing
  - ▶ **Time Domain Multiplexing (TDM)**
  - ▶ **Frequency Domain Multiplexing (FDM)**
    - ▶ Wave length Domain Multiplexing for optical fiber
  - ▶ **Coded Domain Multiplexing (CDM)**
- ▶ Coding
  - ▶ Amplitude Shift Keying (ASK)
  - ▶ Frequency Shift Keying (FSK)
  - ▶ Coded Division Multiple Access (CDMA)

## Code as a third dimension ?

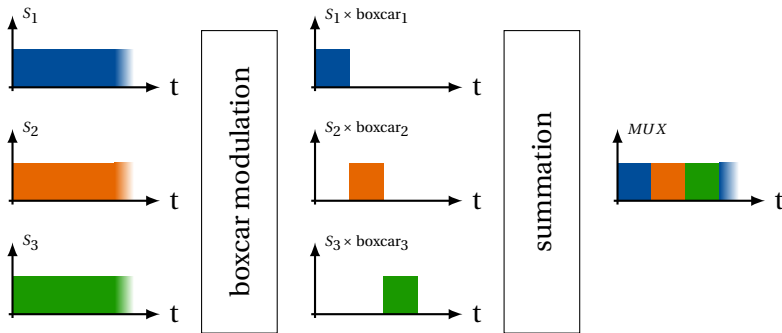


### Multiplexing $\Rightarrow$ spread spectrum

- ▶ Code is represented as a third dimension even if this is **not necessarily a physical dimension**.
- ▶ CDM is usually used to **spread the spectrum** of the multiplexed signal. But the code dimension is often a repartition both in time, in frequency and some times in amplitude.

# Time Domain Multiplexing (TDM)

Time slot of **limited duration** of each input signal ( $S_x$ ) is **summed**

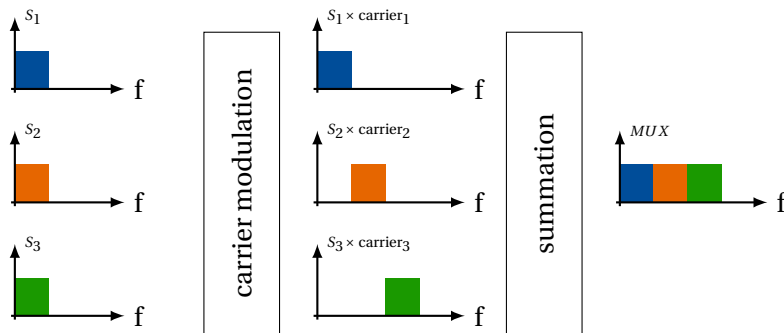


- ▶ Requires a specific boxcar (time shifted) modulation / signal
- ▶ *Limited duration*  $\equiv$  **sampling**

$\Rightarrow$  increasing of the bandwidth  
= risk of noise aliasing

# Frequency Domain Multiplexing (FDM)

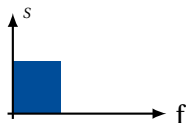
Frequency **transposition** of each input signal ( $S_x$ ) is **summed**



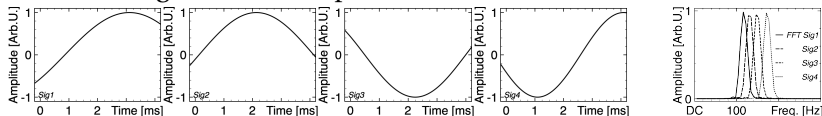
- ▶ Requires a specific frequency carrier / signal
- ▶ *Summation*  $\equiv$  increasing the **bandwidth** and the **dynamic**

# Sine waves multiplexing

until now, signal has been represented as a time or freq. "tophat"

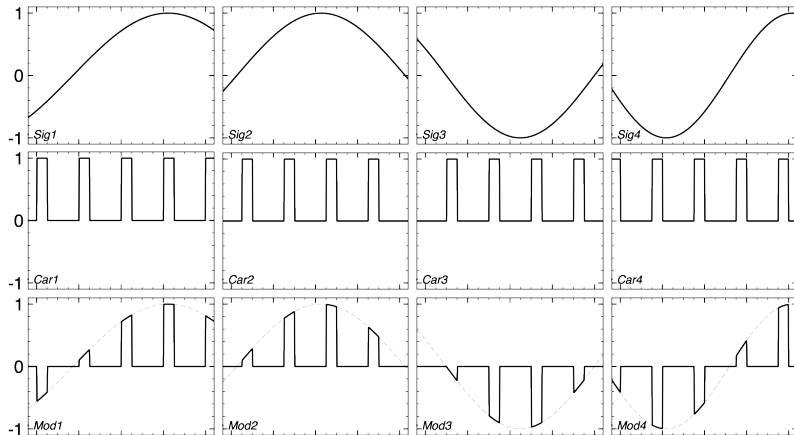


from now, signals will be represented as 4 sine waves



# Time Domain/Division Multiplexing - TDM

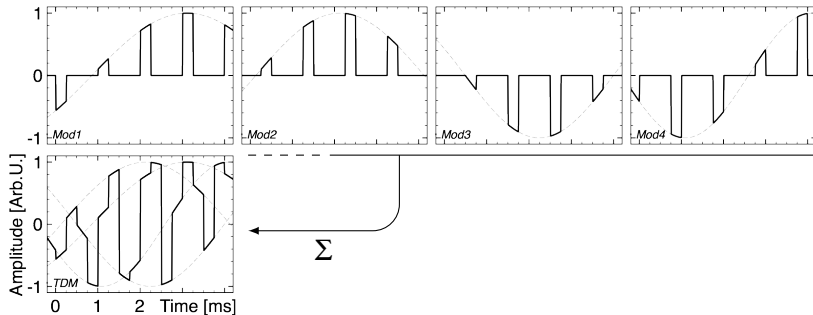
## Modulation - Sampling





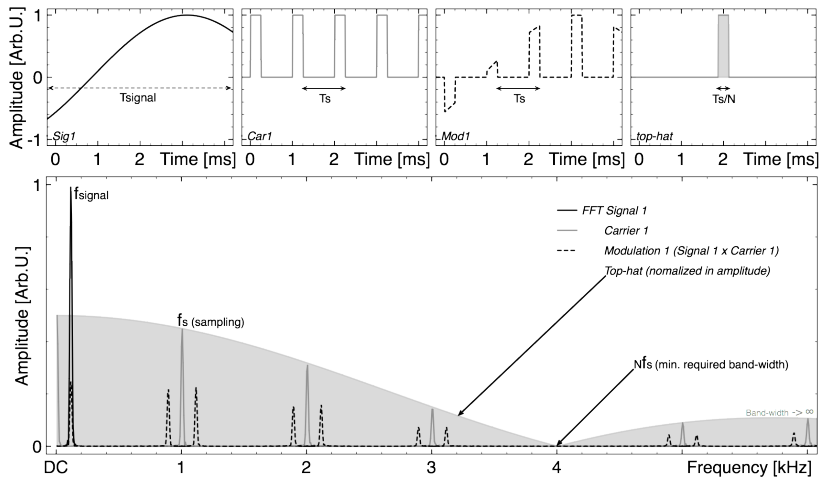
# Time Domain/Division Multiplexing - TDM

## Summation - multiplexing



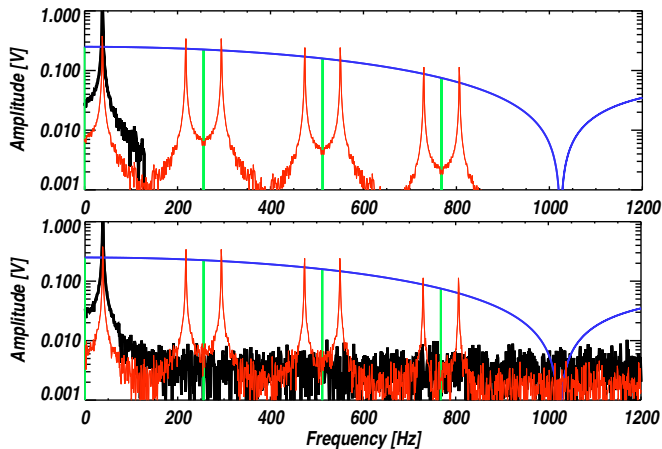
# Time Domain/Division Multiplexing - TDM

Spectrum occupancy :  $BW_{TDM} > N \times f_s > 2 \times N \times BW_{Sig}$



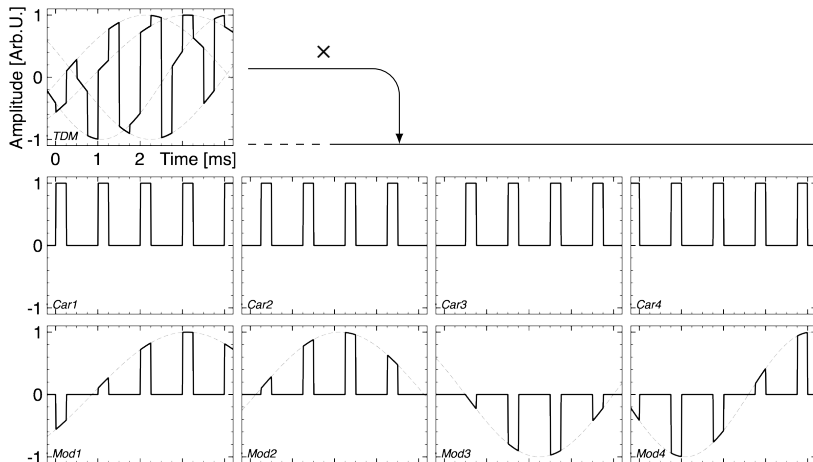
# Time Domain/Division Multiplexing - TDM

Shannon-Nyquist Unsatisfied  $\Rightarrow$  Alias the unfiltered white noise



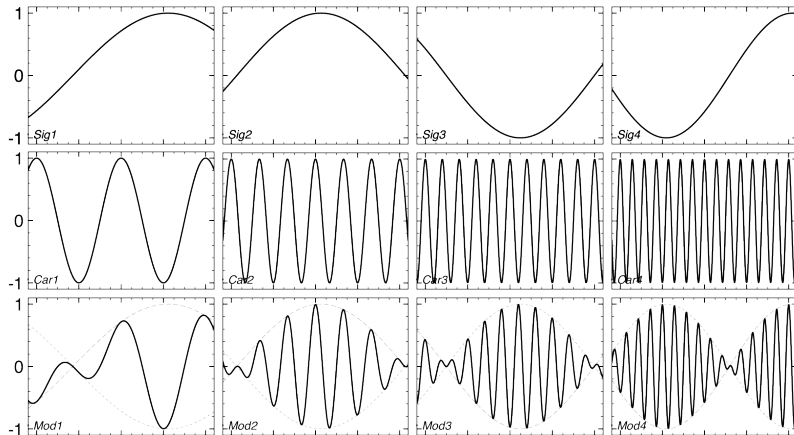
# Time Domain/Division Multiplexing - TDM

demultiplexing before sample & hold and filtering



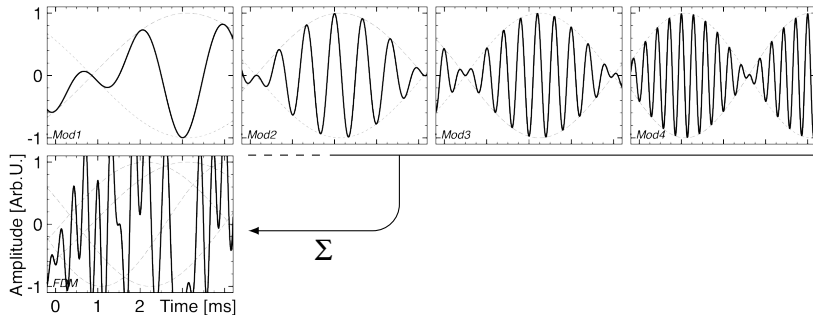
# Frequency Domain/Division Multiplexing - FDM

## Modulation - Frequency transposition



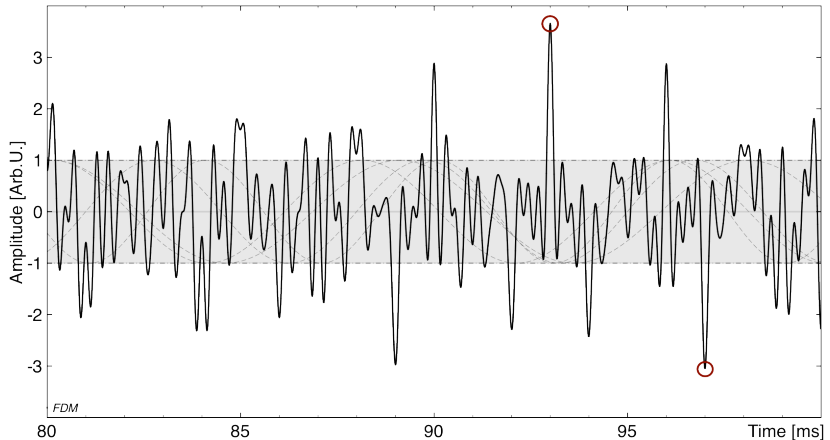
# Frequency Domain/Division Multiplexing - FDM

## Summation - multiplexing



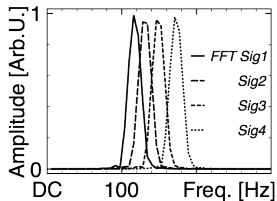
# Frequency Domain/Division Multiplexing - FDM

Increasing of the amplitude of the multiplexed signal

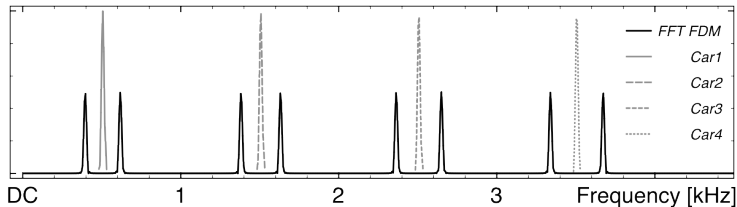


# Frequency Domain/Division Multiplexing - FDM

Spectrum occupancy :  $BW_{FDM} > 2 \times N \times BW_{Sig}$

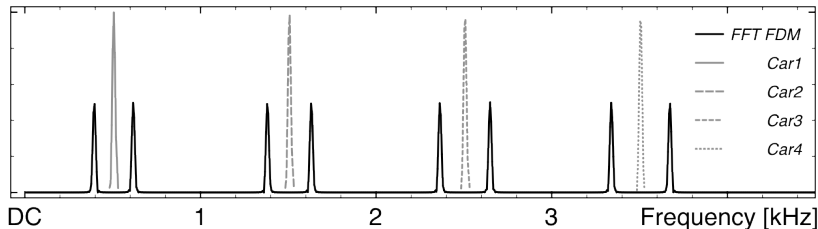


Multiplexing





# Frequency Domain/Division Multiplexing - FDM

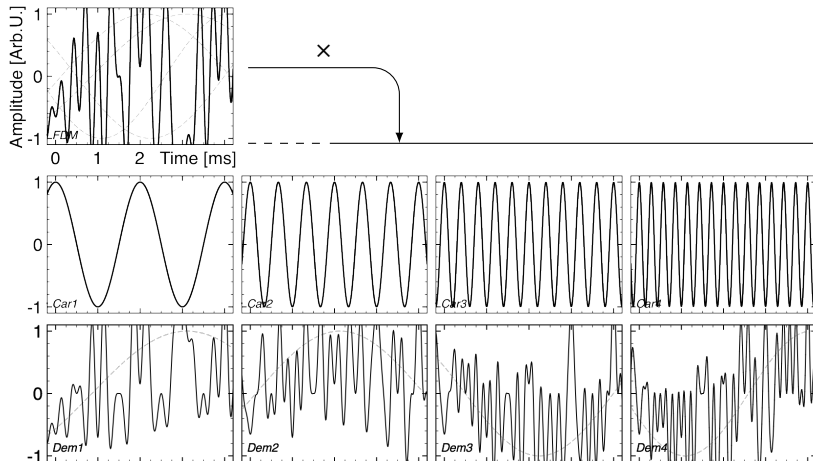


## Aliasing of the unfiltered signal and white noise

As for TDM, there is a "Shannon-Nyquist" law (modulation *vs* sampling) which need to limit the signal (and noise) to a bandwidth below an half of the carriers frequency separation

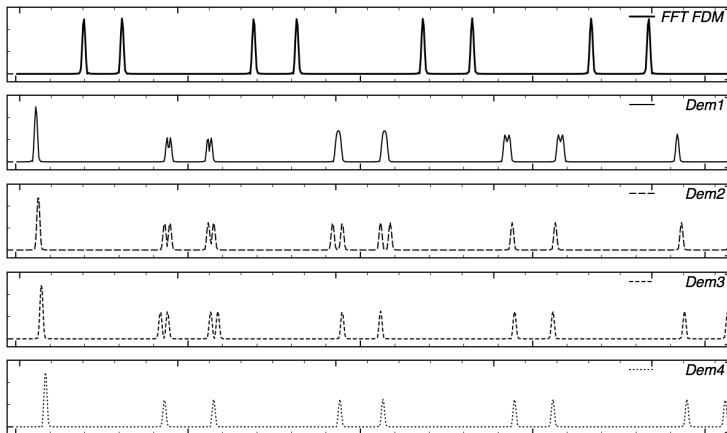
# Frequency Domain/Division Multiplexing - FDM

demultiplexing before filtering



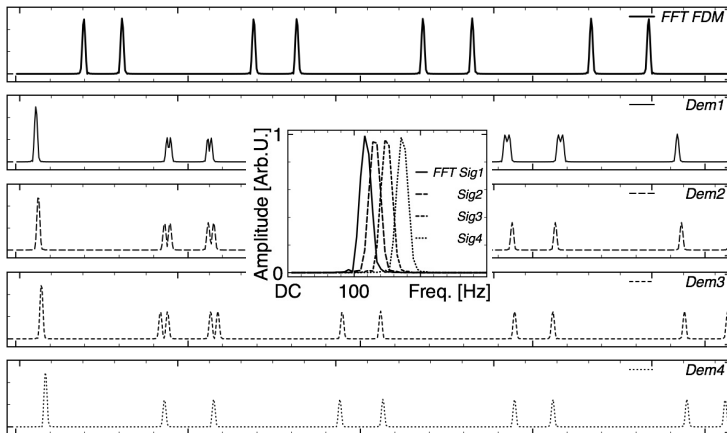
# Frequency Domain/Division Multiplexing - FDM

demultiplexing in the frequency domain



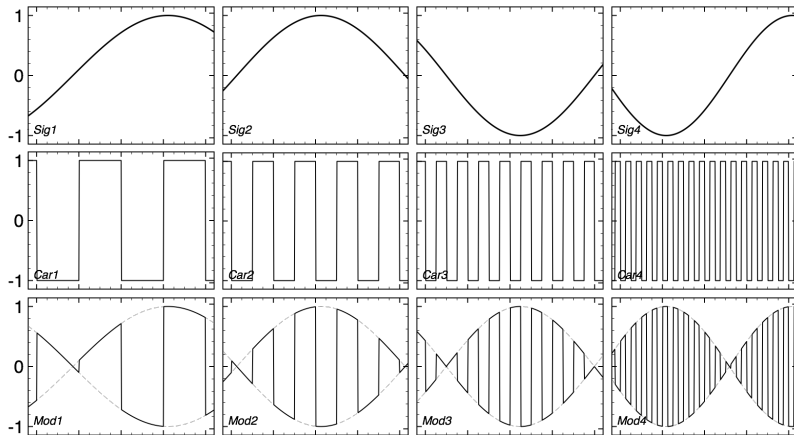
# Frequency Domain/Division Multiplexing - FDM

demultiplexing in the frequency domain



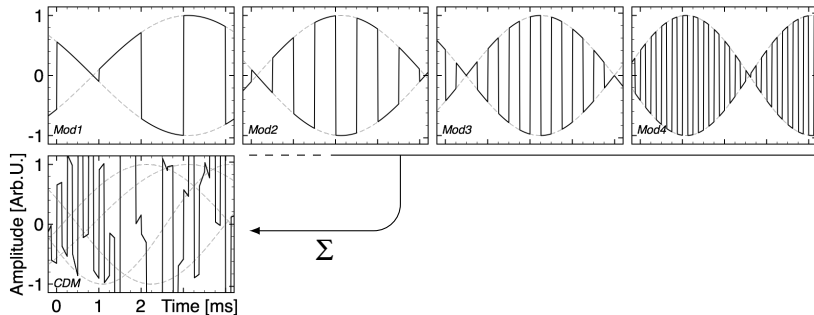
# Coded Domain/Division Multiplexing - CDM

Modulation - "Coding" (not the Walsh code)



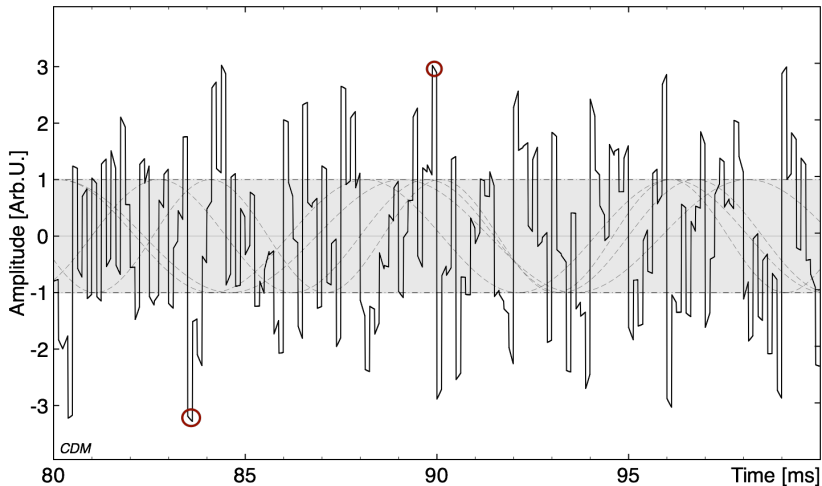
# Coded Domain/Division Multiplexing - CDM

## Summation - multiplexing



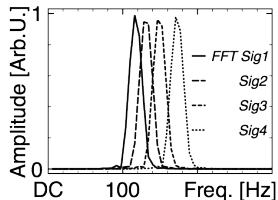
# Coded Domain/Division Multiplexing - CDM

Increasing of the amplitude of the multiplexed signal

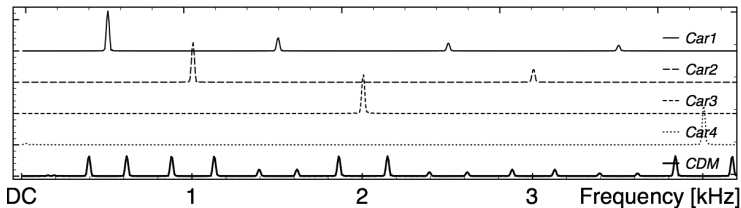


# Coded Domain/Division Multiplexing - CDM

Spectrum occupancy :  $BW_{FDM} > 2 \times N \times BW_{Sig}$



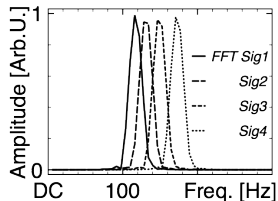
Multiplexing



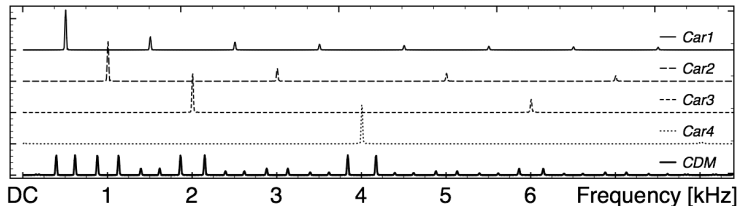


# Coded Domain/Division Multiplexing - CDM

Spectrum occupancy: wide "spread" spectrum

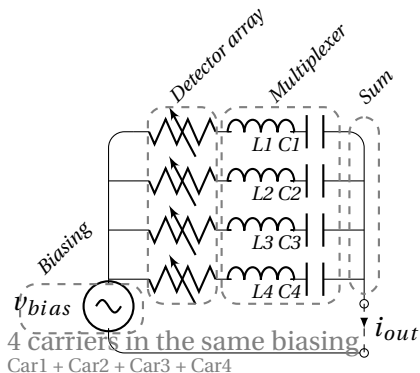
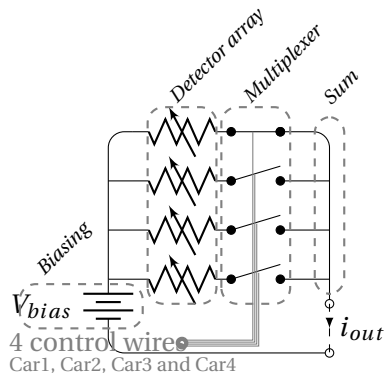


Multiplexing



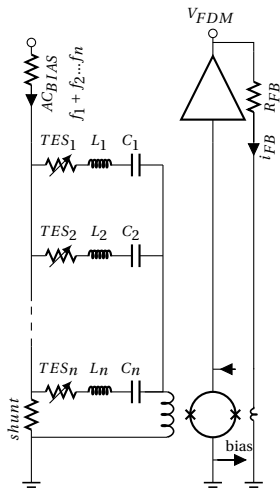
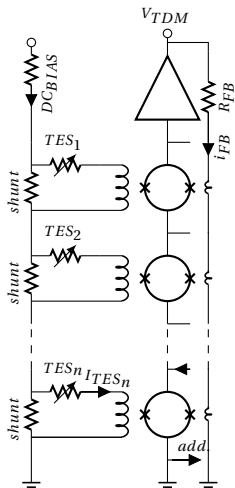
# TDM vs FDM principle

## Multiplexer 1D

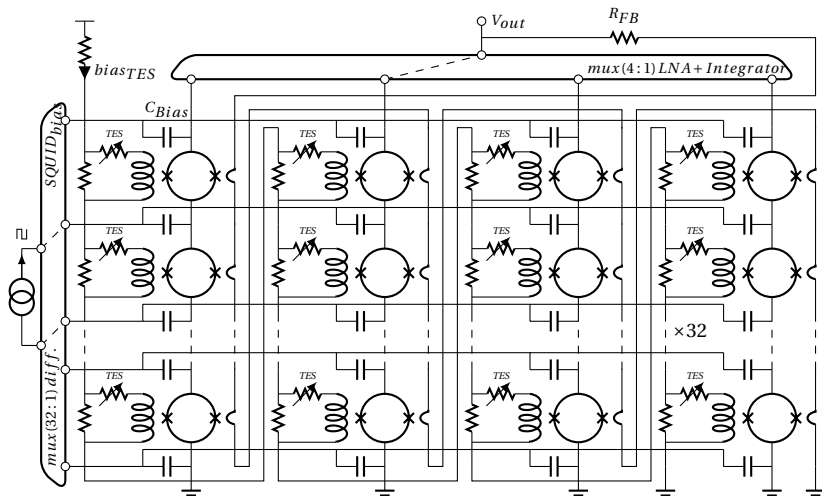


# TDM vs FDM with SQUID 1D

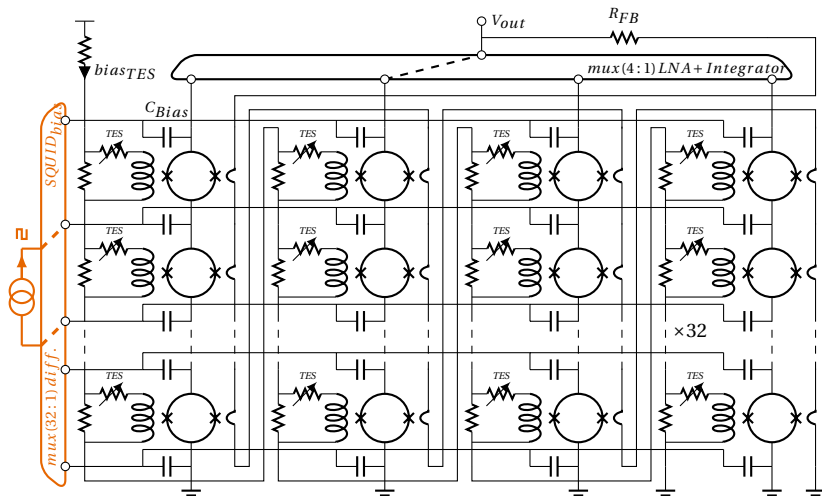
## Multiplexer 1D



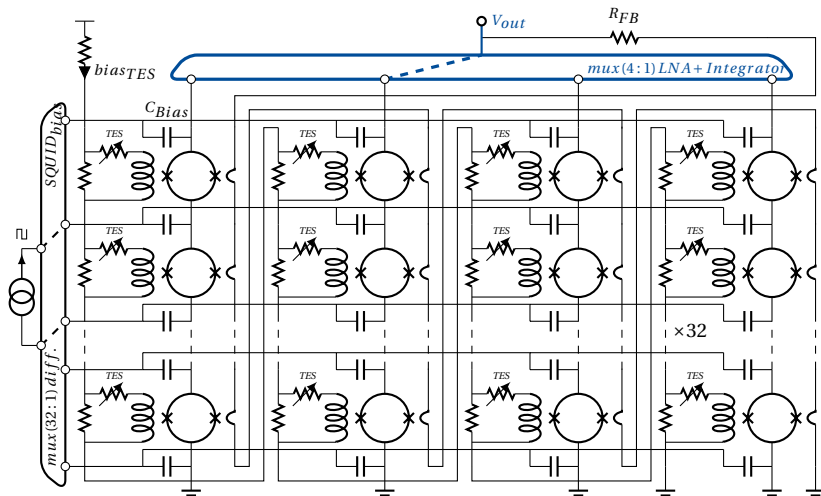
## Cryogenic TES time domain multiplexer - QUBIC



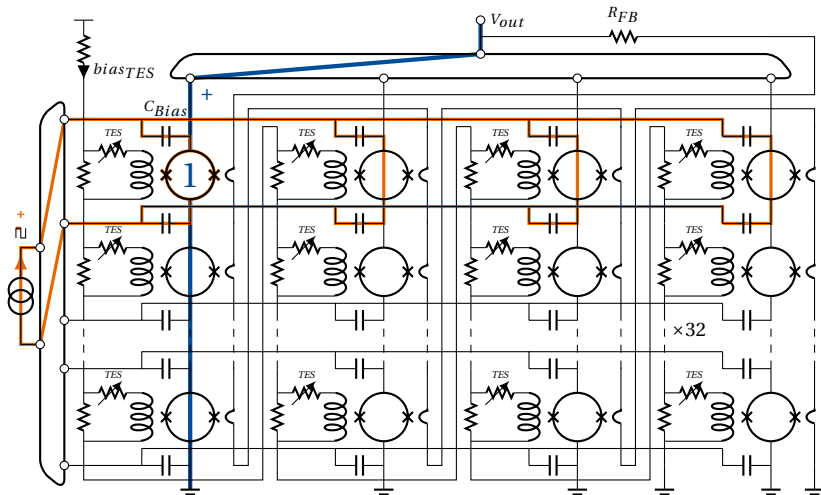
## Cryogenic TES time domain multiplexer - QUBIC



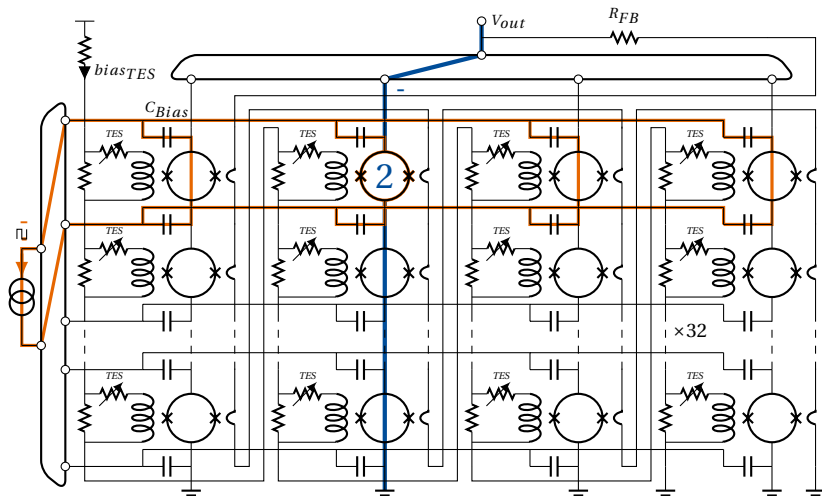
## Cryogenic TES time domain multiplexer - QUBIC



# Cryogenic TES time domain multiplexer - QUBIC

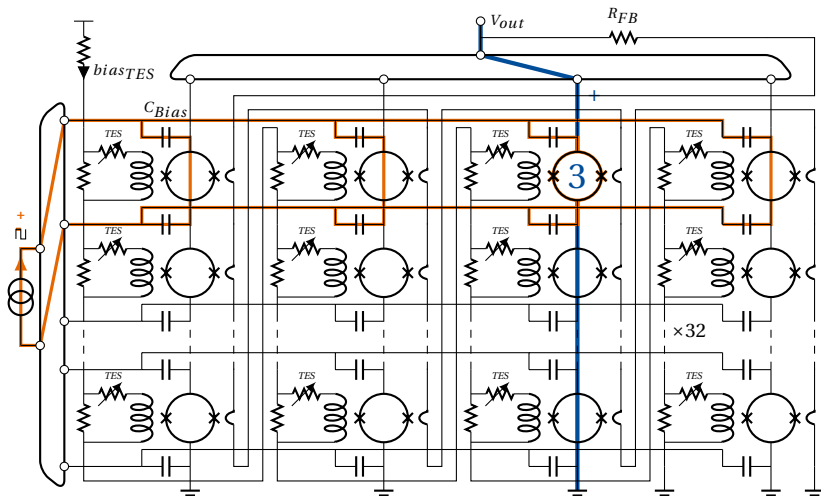


## Cryogenic TES time domain multiplexer - QUBIC



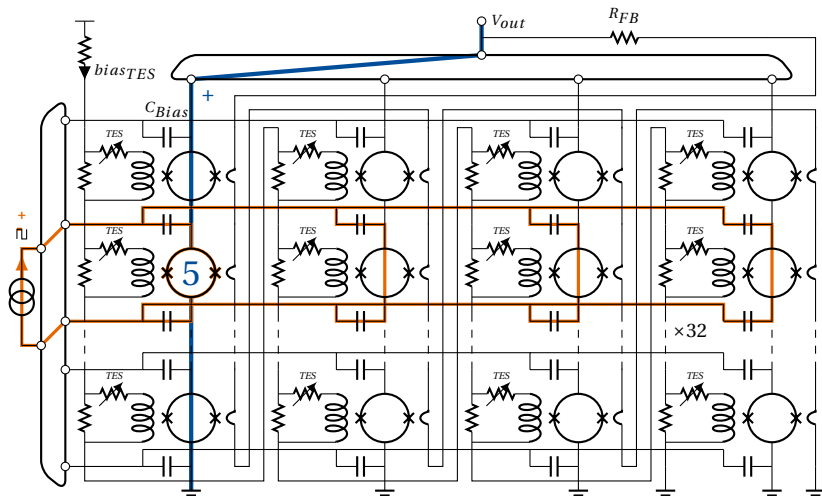


# Cryogenic TES time domain multiplexer - QUBIC

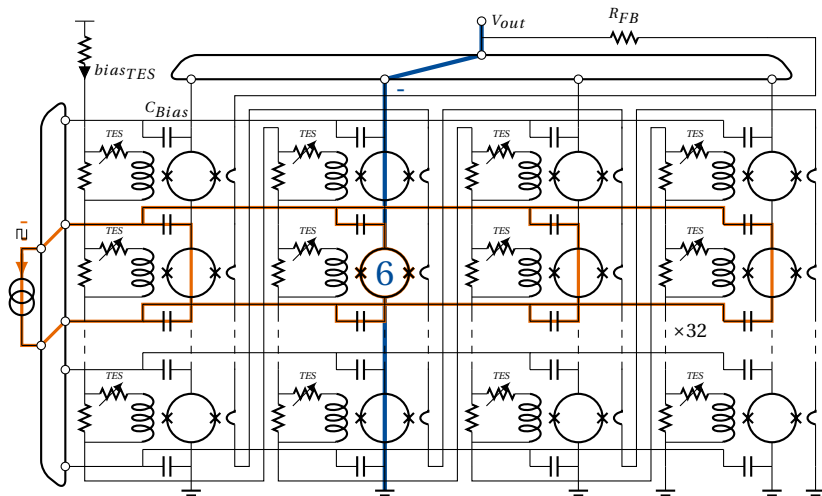




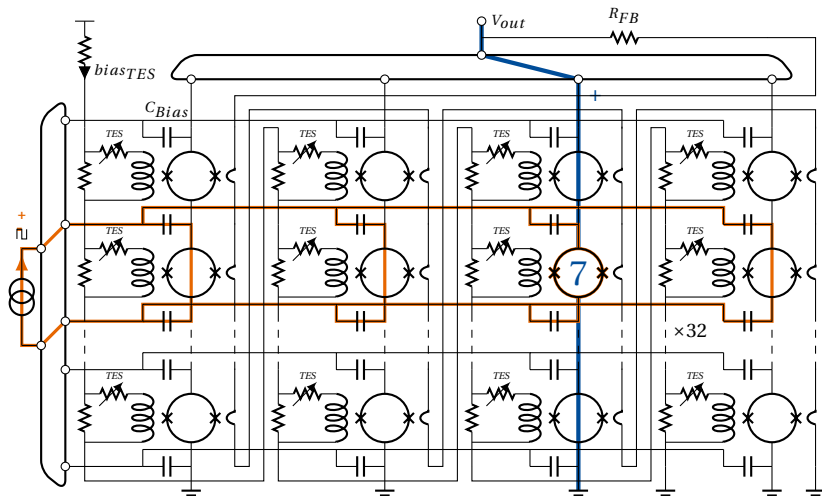
## Cryogenic TES time domain multiplexer - QUBIC



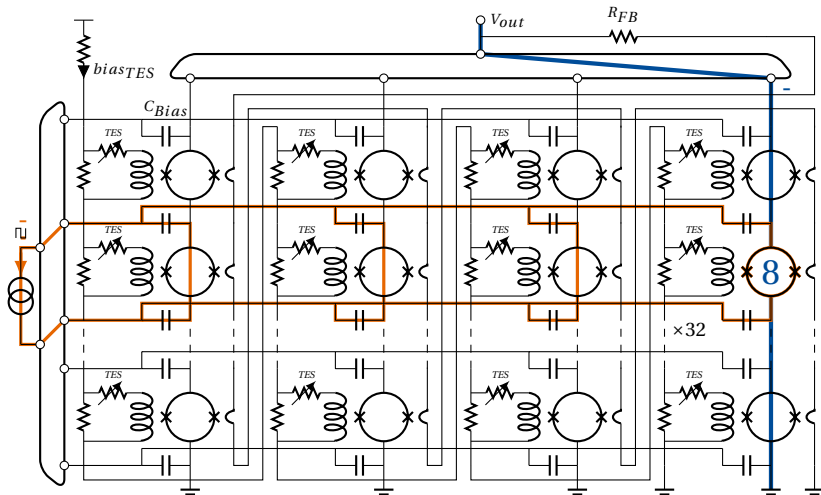
# Cryogenic TES time domain multiplexer - QUBIC



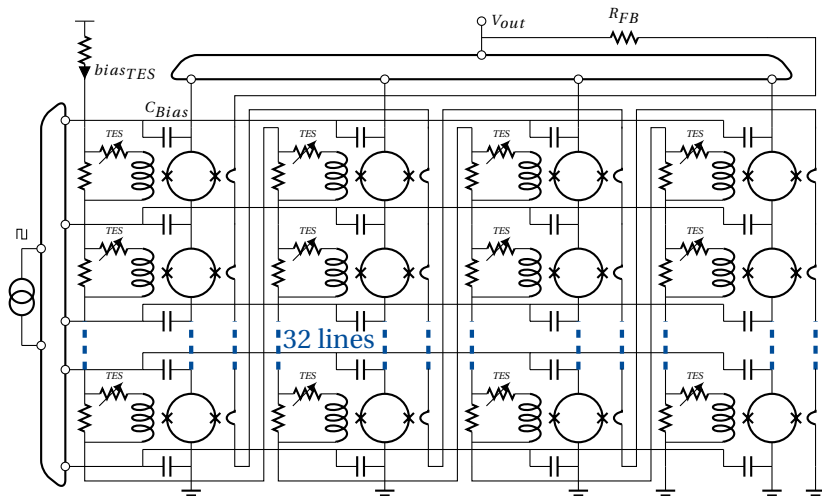
## Cryogenic TES time domain multiplexer - QUBIC



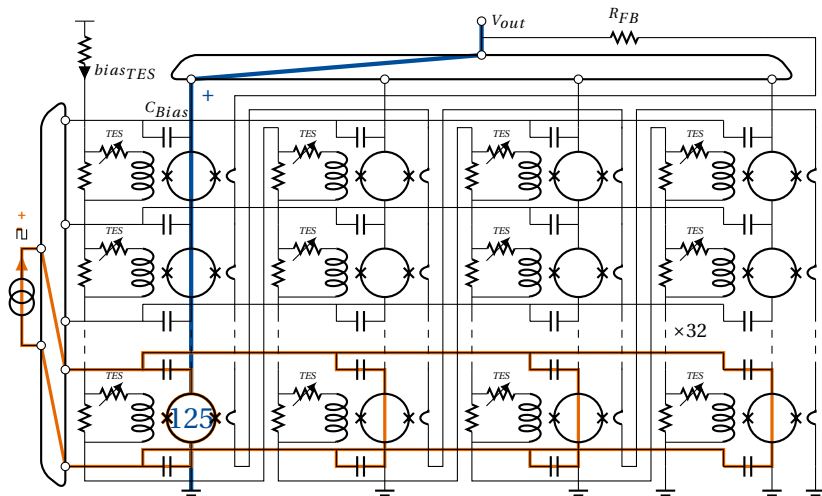
# Cryogenic TES time domain multiplexer - QUBIC



# Cryogenic TES time domain multiplexer - QUBIC

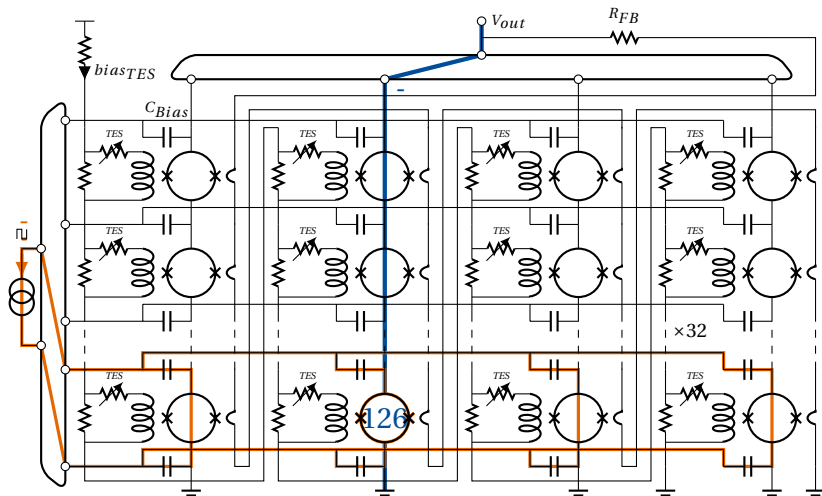


## Cryogenic TES time domain multiplexer - QUBIC

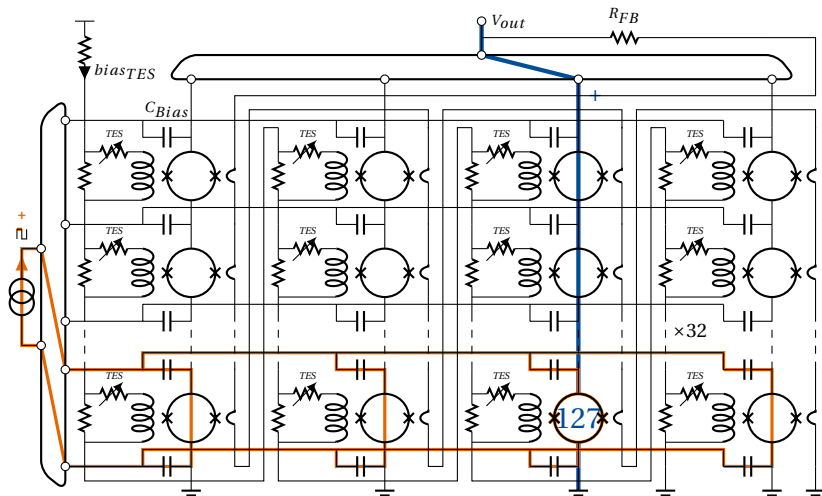




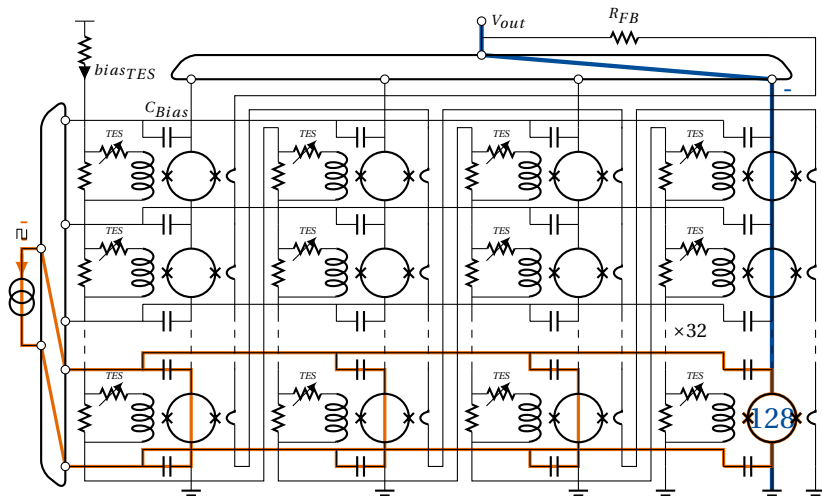
## Cryogenic TES time domain multiplexer - QUBIC



## Cryogenic TES time domain multiplexer - QUBIC

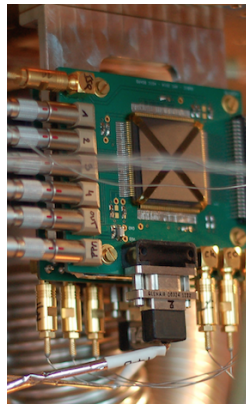
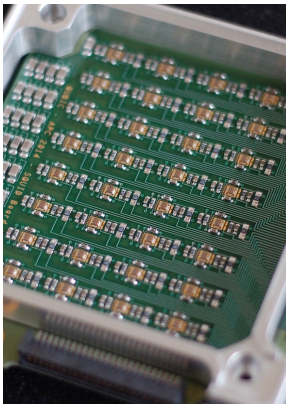
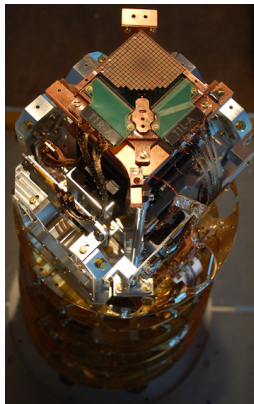


## Cryogenic TES time domain multiplexer - QUBIC



# Cryogenic TES time domain multiplexer - QUBIC

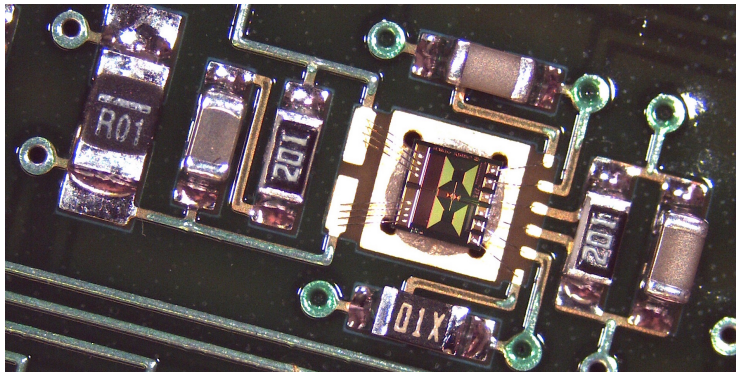
QUBIC readout chaîne : TES (300 mK) + SQUID (1K) + ASIC (77K)



*Correlated sampling on blind thermometers to remove 1/f noise*

## SQUID glued and wire bonded on a PCB

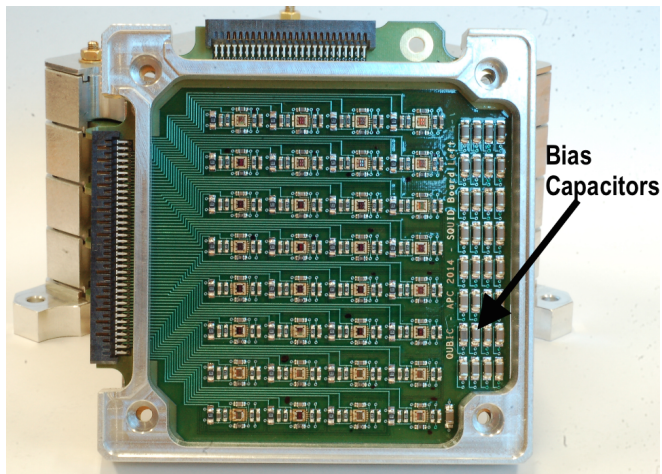
StarCryoelectronics SQ680 specific design.



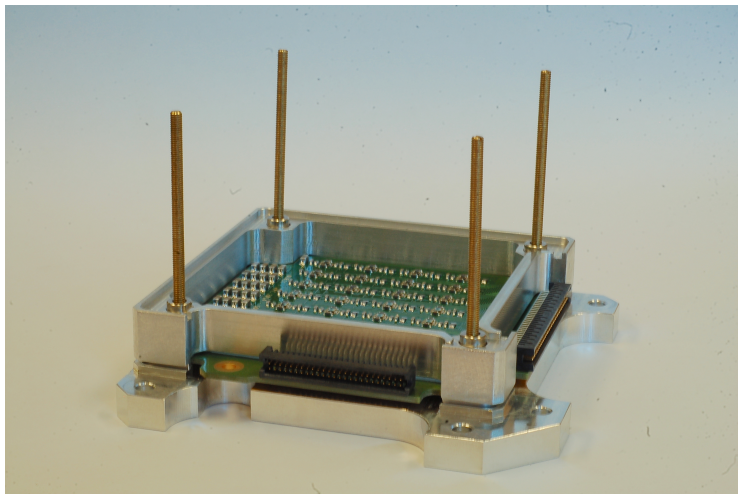
Solder plated track (no parasitic resistances)

Shunt resistor and filter devices

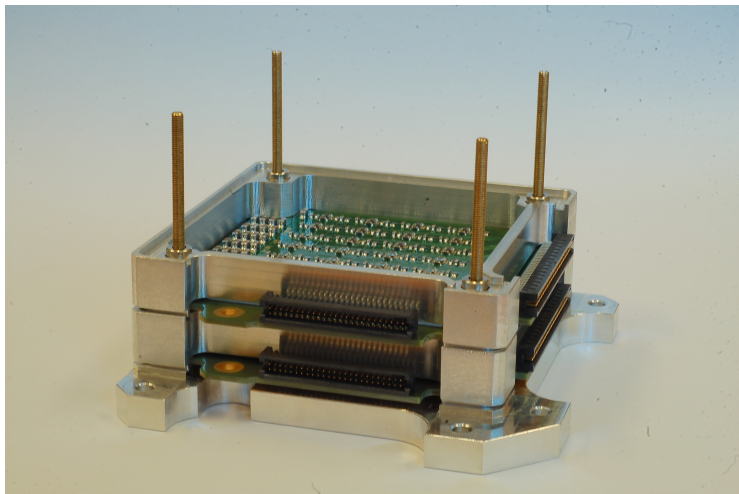
## 32 SQUIDs glued and wire bonded on a PCB



## 32 SQUIDs glued and wire bonded on a PCB

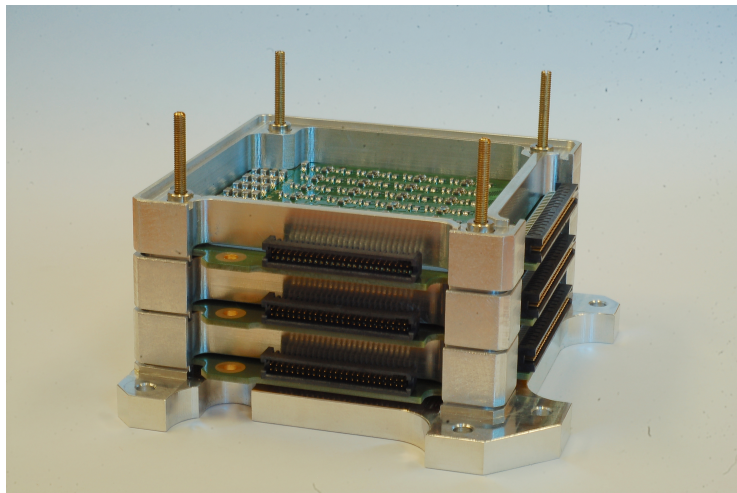


## 64 SQUIDs glued and wire bonded on a PCB

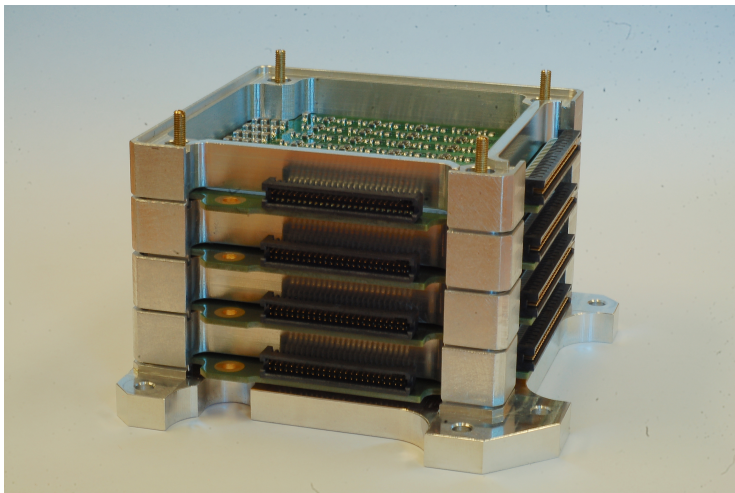




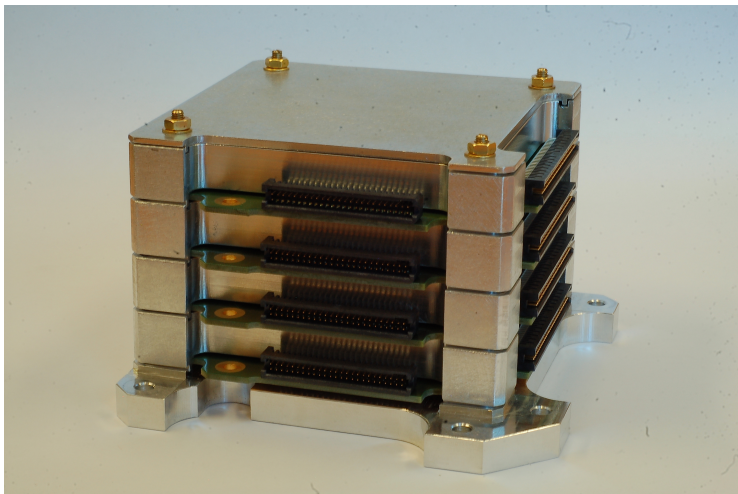
## 96 SQUIDs glued and wire bonded on a PCB



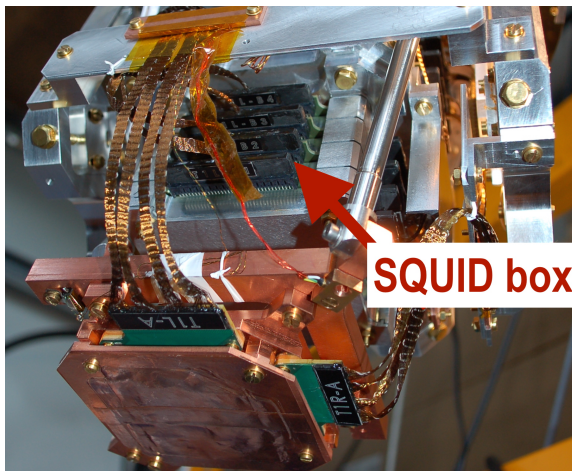
## 128 SQUIDs glued and wire bonded on a PCB



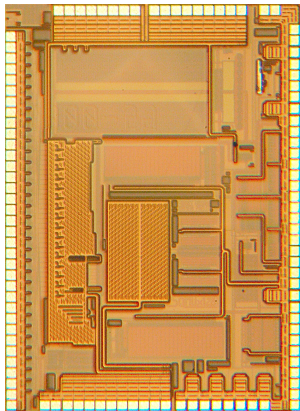
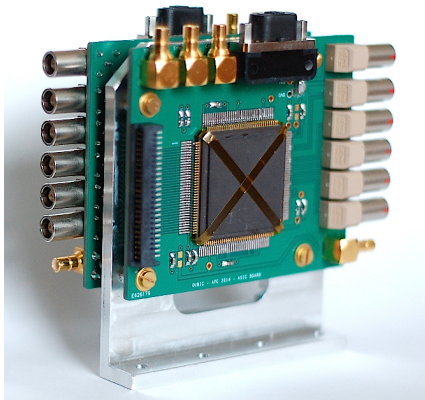
## 128 SQUIDs glued and wire bonded on a box



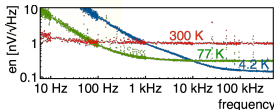
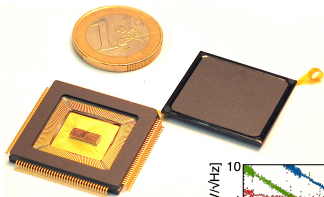
## SQUIDs glued and wire bonded on a box



## ASIC Stage (Application Specific Integrated Circuit)



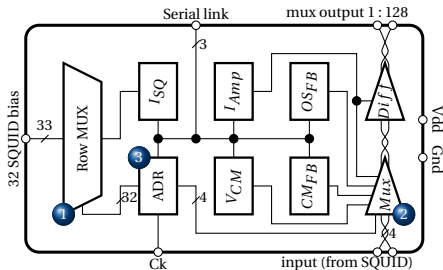
## SiGe ASIC for cryogenic 1:128 TD SQUID M



## BiCMOS SiGe ASIC

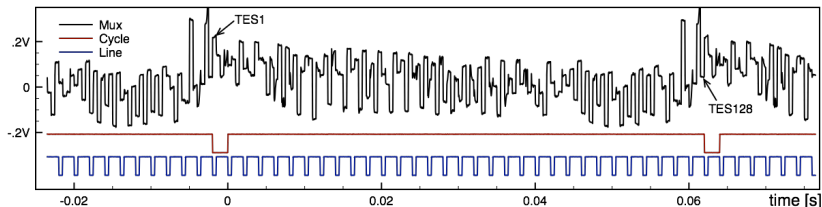
350nm AMS technology

1. SQUID rows addressing:  
Biasing through capacitors with AC multiplexed current sources (1 : 32)
2. Low noise amplifier with multiplexed inputs:  
FLL preamplifier  
column mux. (1 : 4)
3. Digital addressing circuit  
controlled by external Ck



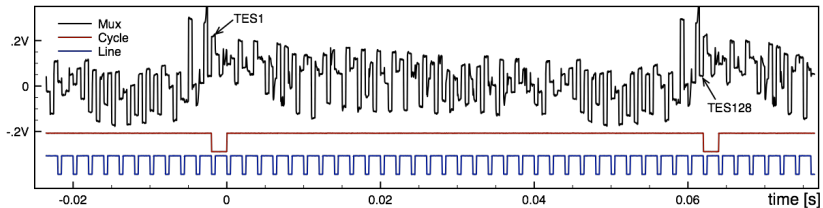
# Multiplexed time line

## 1:128 multiplexing rate

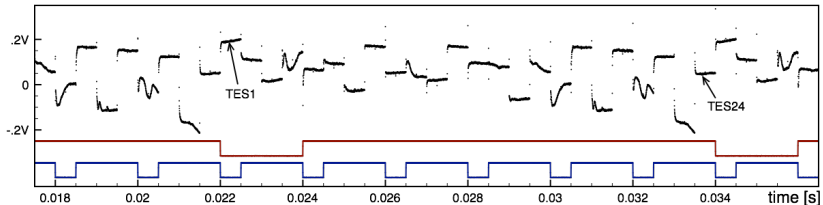


# Multiplexed time line

## 1:128 multiplexing rate



The ASIC allows to **reduce the part of the array readout**

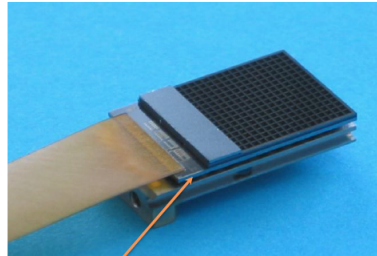
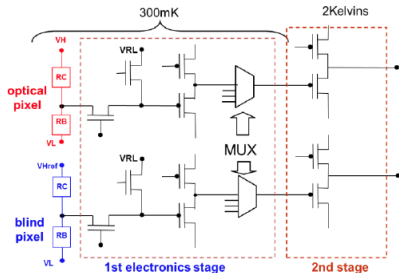




## 300 mK CMOS 1:16 TDM - PACS/Herschel satellite



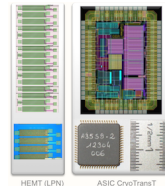
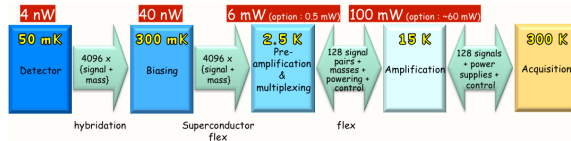
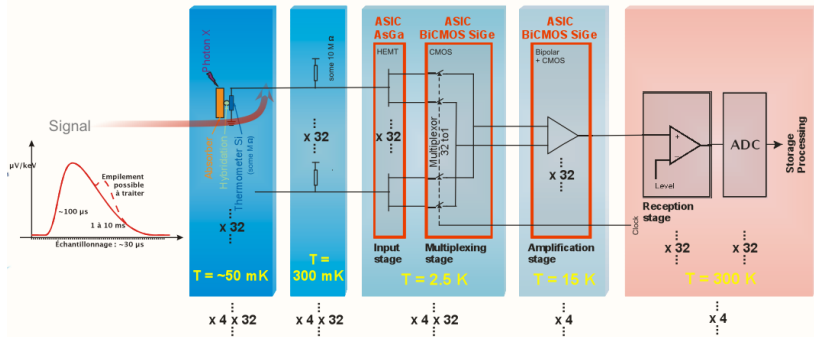
- ▶ **Double correlated sampling** to remove  $1/f$  readout noise
- ▶ **Differential** measurement with blind pixels to remove the external collective perturbations.



cold electronics layer

P. Agnès, L. Rodriguez, L. Vigroux et al. - CEA

# Xray microcalorimeter + TDM (HEMT + SiGe)

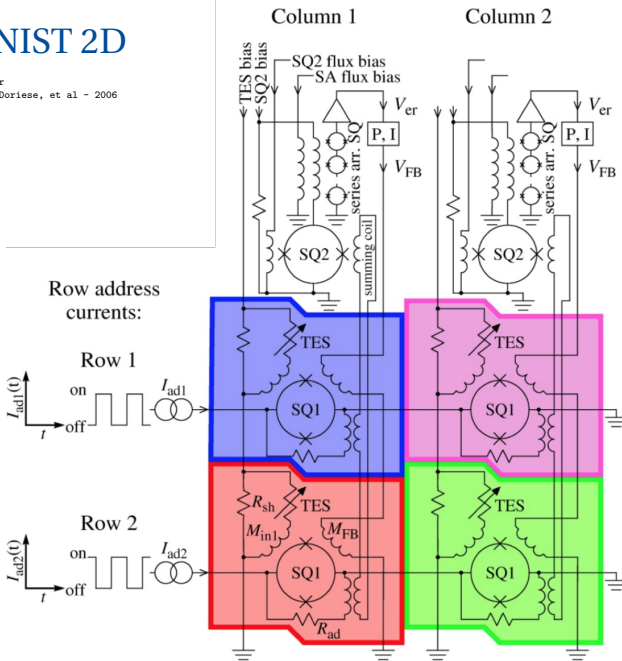


X. de le Broise et al. - CEA SEDI

# TDM by NIST 2D

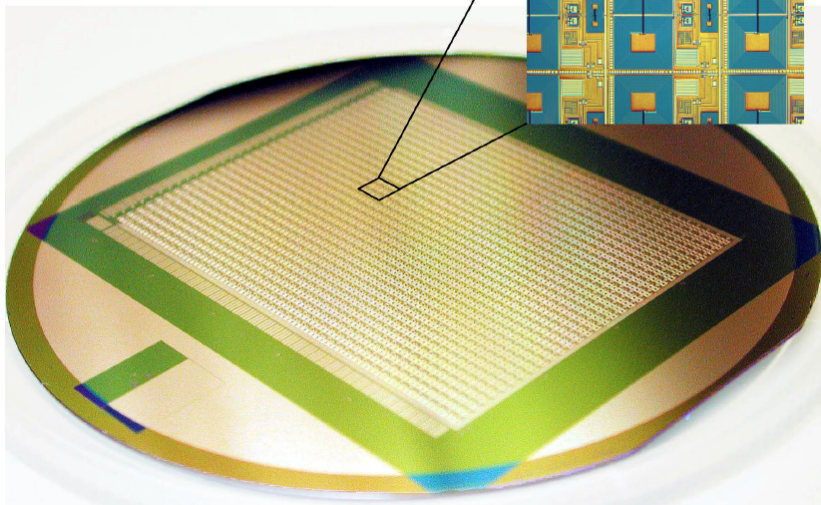
SQUID Multiplexer

- G. Hilton, R. Doriese, et al - 2006

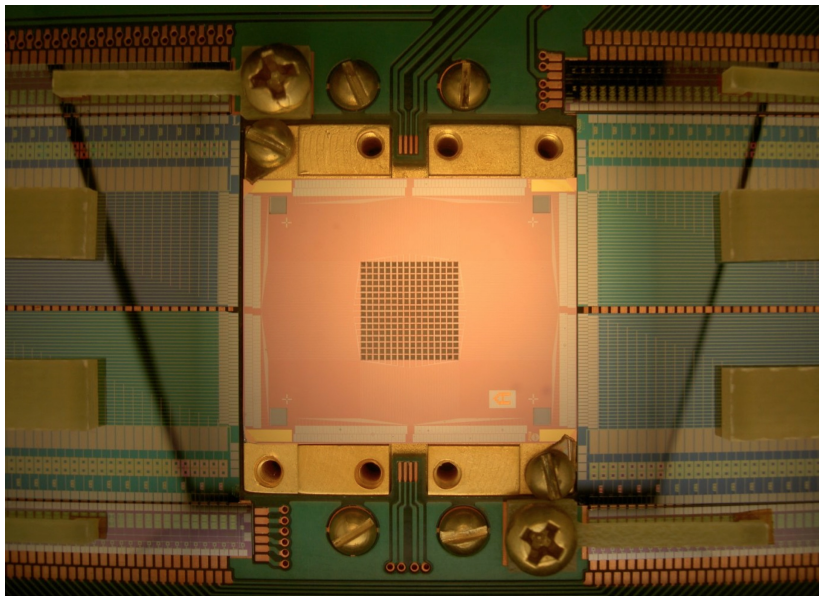


## TDM SCUBA2 SQUID Chip

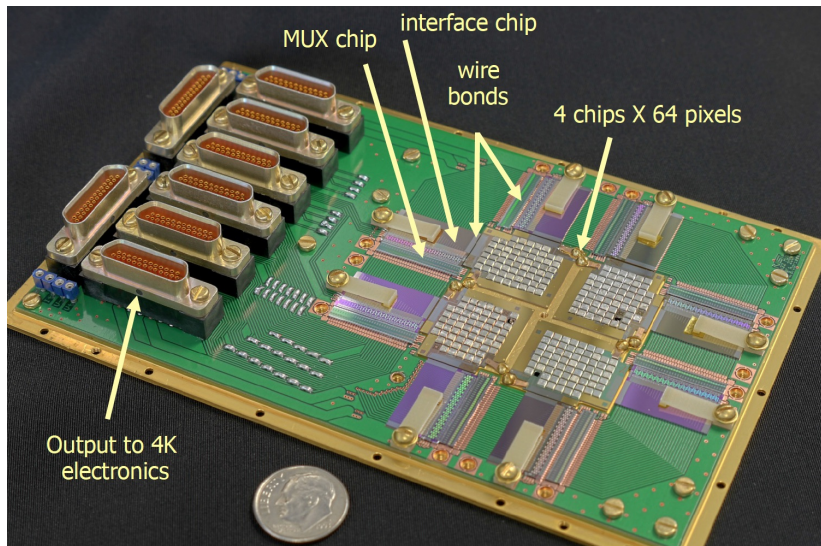
Wafer-scale processing assembled with indium bump-bonding on a TES array of 40x32 pixels



## TDM TES X-ray mux - 4x32 - 256 detectors

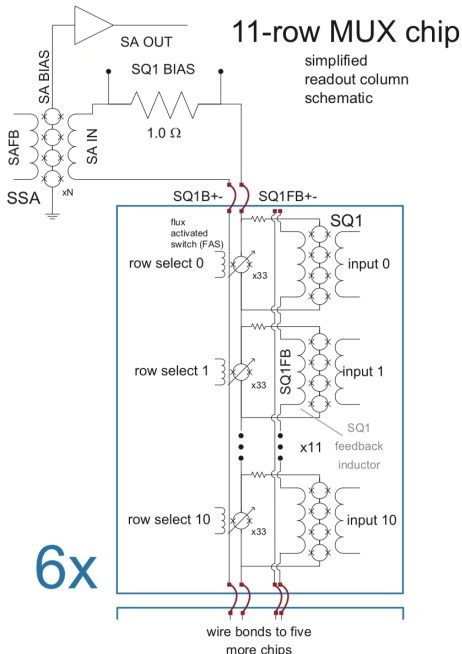


# TDM TES $\gamma$ -ray mux



# TDM with SQ1/FAS

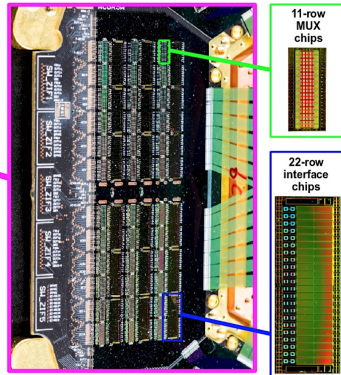
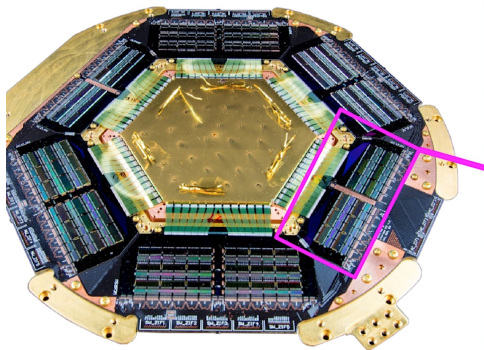
Readout of two-kilopixel TES arrays for Advanced ACTPol 32  
 Each SQ1 is shunted by a flux activated switch (FAS)



# TDM ACTpol Focal Plan

32 columns of 64 TESEs

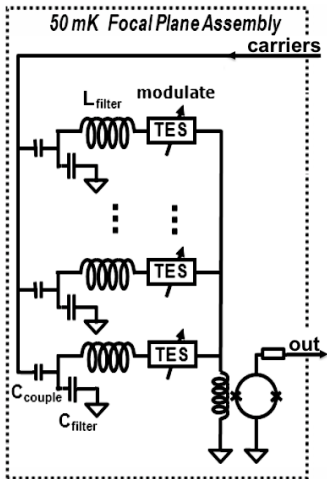
Each SQ1 is shunted by a flux activated switch (FAS)



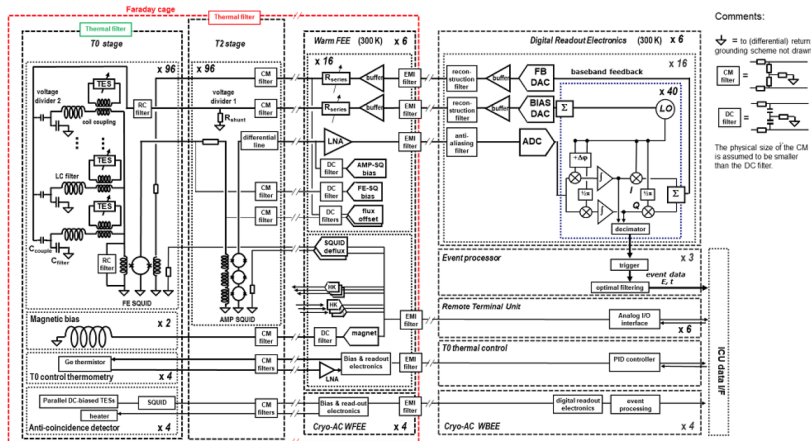
Readout of two-kilopixel transition-edge sensor arrays for Advanced ACTPol - S. W. Henderson et al.



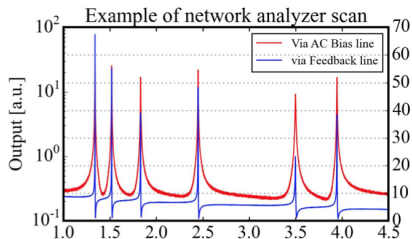
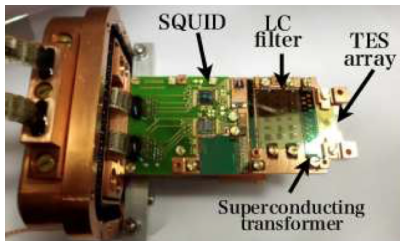
# FDM by SRON 1D



# FDM by SRON 1D with BaseBand FeedBack

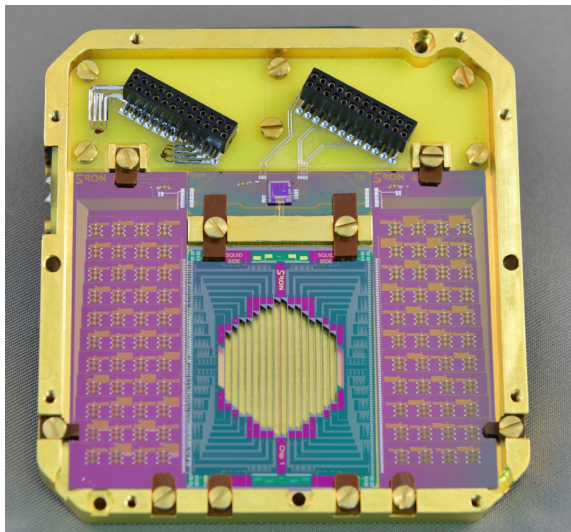


# FDM by SRON 1D ATHENA X-IFU demonstrator

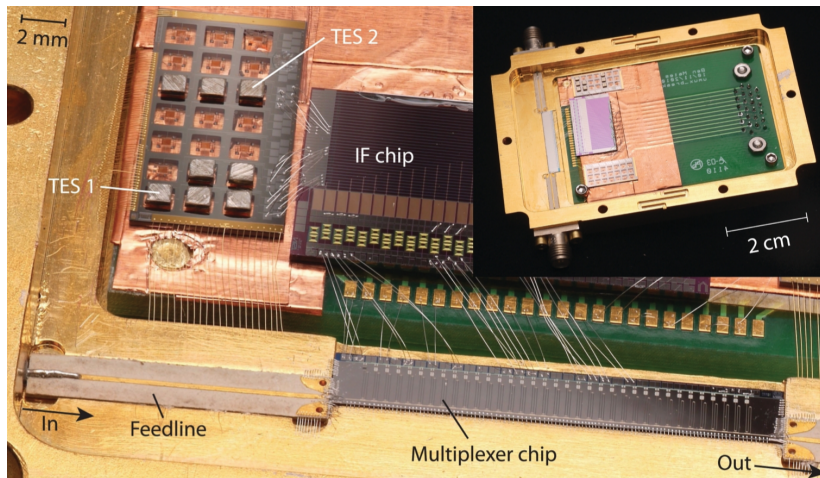


Development of FDM for the X-ray Integral Field Unit (X-IFU) on the Athena - H. Akamatsu et al.  
- 2016

# FDM by SRON 1D for the far-infrared satellite mission SPICA

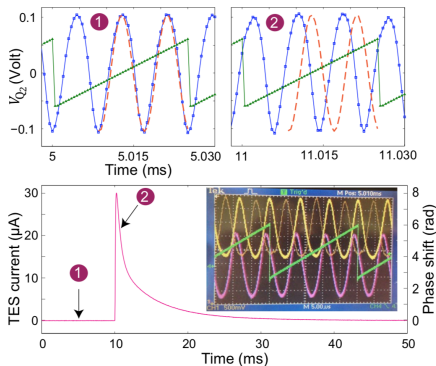
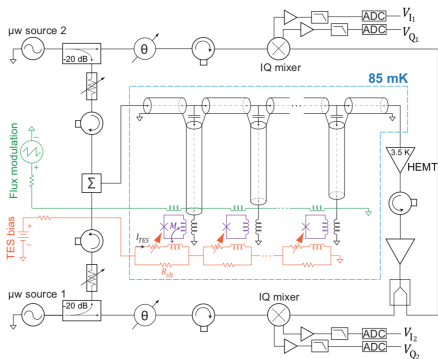


# Microwave SQUID multiplexing - NIST



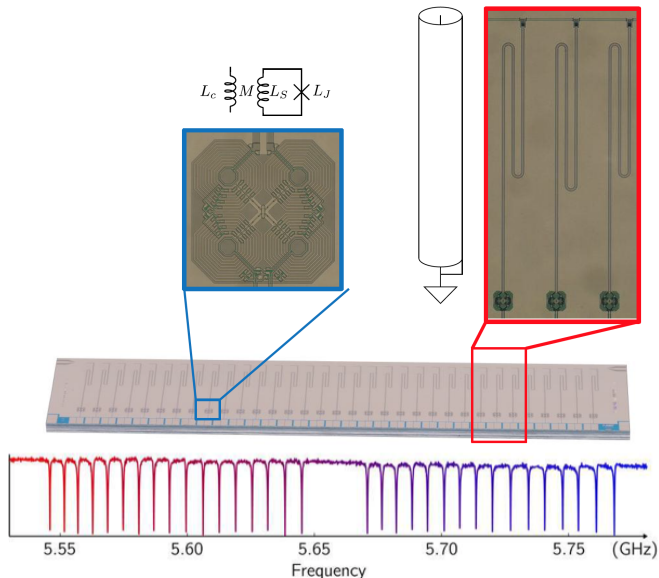
High-resolution gamma-ray spectroscopy with a microwave-multiplexed transition-edge sensor array

# Microwave SQUID multiplexing - NIST

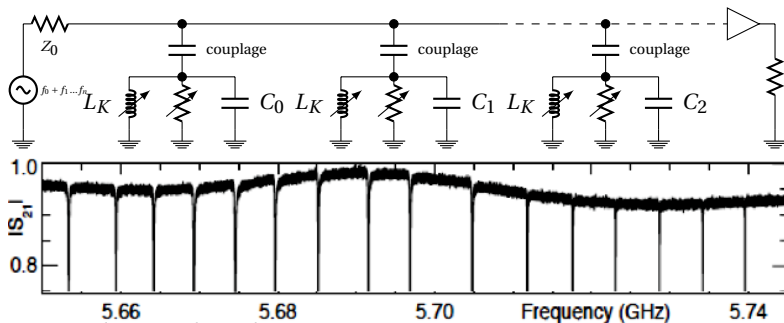


High-resolution gamma-ray spectroscopy with a microwave-multiplexed transition-edge sensor array  
*Multiplexing capability of MKIDs / DC biased - Irwin et al.*

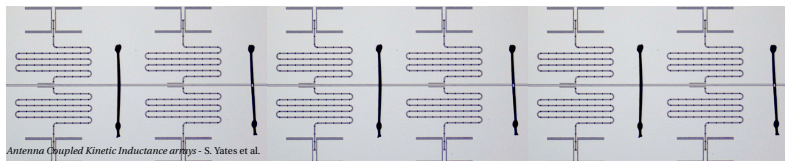
# Microwave SQUID multiplexing - NIST



## KID multiplexing



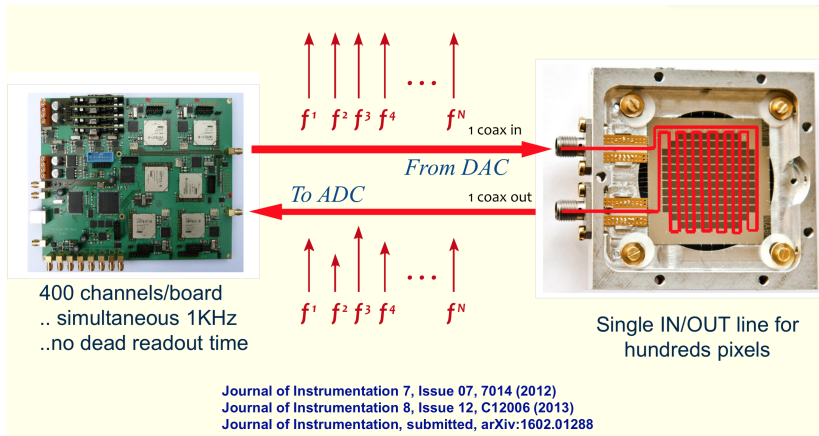
Microwave Kinetic Inductance Detectors: The First Decade - B. Mazin



Antenna Coupled Kinetic Inductance arrays - S. Yates et al.

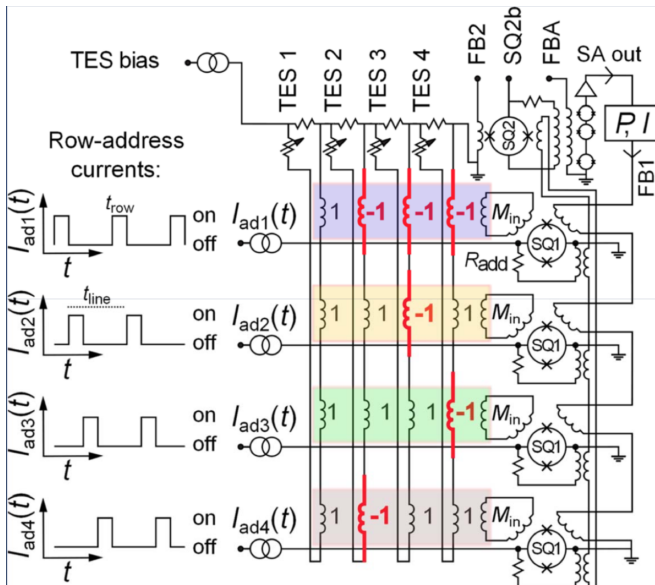


## KID/FDM by NEEL

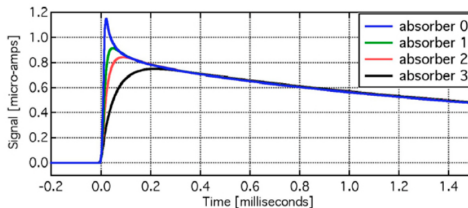
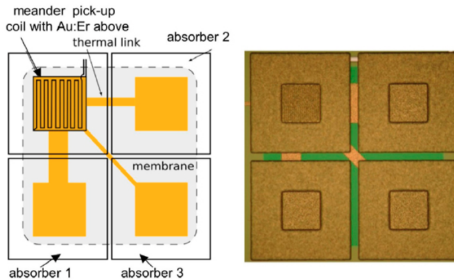


NIKA and NIKA2: from the pathfinder KID camera to the ultimate mm-wave imaging/polarimetry at the 30-meters Pico Veleta telescope - A. Monfardini - 2017

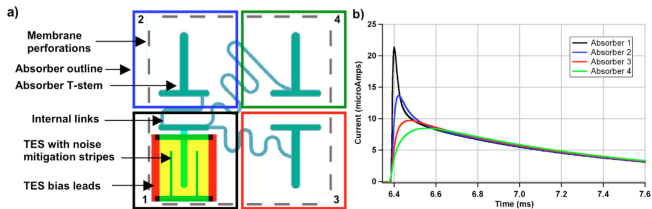
## CDM by NIST 1D



# Thermal Mux



# Thermal Mux



4-pixel Hydra - Generation-X Microcalorimeter Development & Roadmap

# Conclusion

- ▶ Multiplexing for the readout of large arrays

## Reduction of the wiring

- ▶ The multiplexer must have better :

- ▶ **bandwidth**  $> 2 \times N \times BW_{Sig}$ ,
- ▶ **dynamic range** and/or
- ▶ **noise performances**  $\propto \sqrt{N}$ .

than for a readout of one pixel

- ▶ Multiplexing is like a modulation + summation

- ▶ **TDM is based on "boxcar" modulation**

Switchs or shift

- ▶ **FDM is based carrier modulation**

LC filters

- ▶ + lot of "new" Mux as CDM,  $\mu$ Mux, Thermal Mux ...