

# 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*

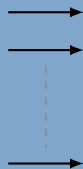
Techno. review

# Multiplexing general

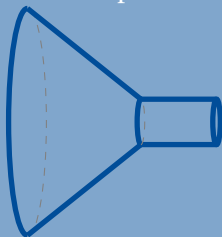
Transmission of  $N$  signals over 1 channel

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 :

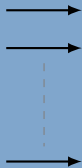
*several telephone calls may be carried using one wire*

# Multiplexing general

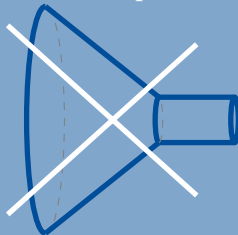
Transmission of  $N$  signals over 1 channel

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"

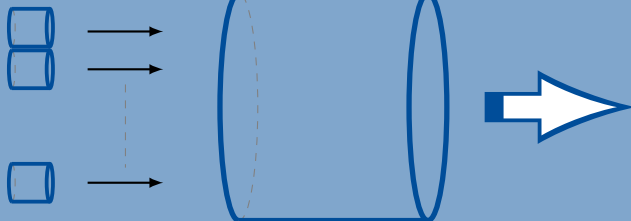
INFORMATION

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.

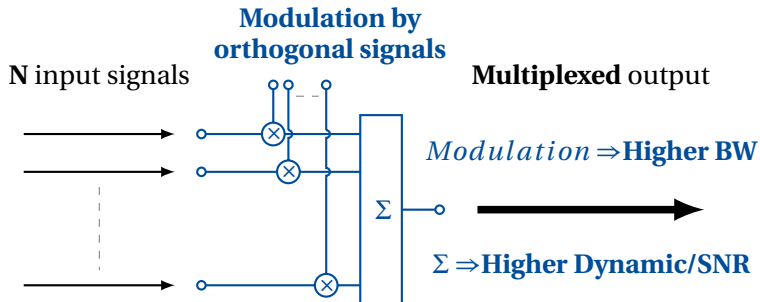
- ⇒ The increasing of the required performances is directly linked to the number N of multiplexed signals.
- ⇒ The affected performances are both :
  - ▶ Band Width
  - ▶ Dynamic / Signal to Noise Ratio

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:**

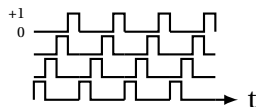


Orthogonal : **boxcar functions** or **carriers at different frequencies.**

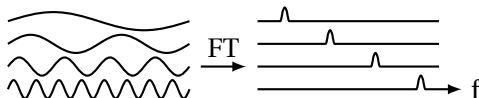
Orthogonality ⇒ demultiplexer **able to recover each input signal without interference from the other.**

# Orthogonal functions

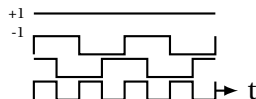
- ▶ boxcar functions  $\equiv$  **sampling**



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



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

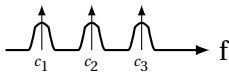


\* as used for error-detection/correction code. Especially, Hadamard/Walsh code could be used for multiplexing.

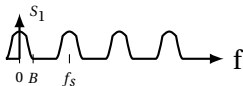
# limitations

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**.

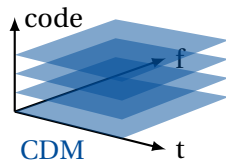
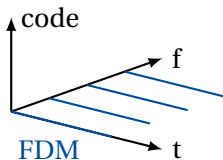
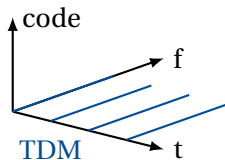
than for a readout of one pixel.

*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 ?

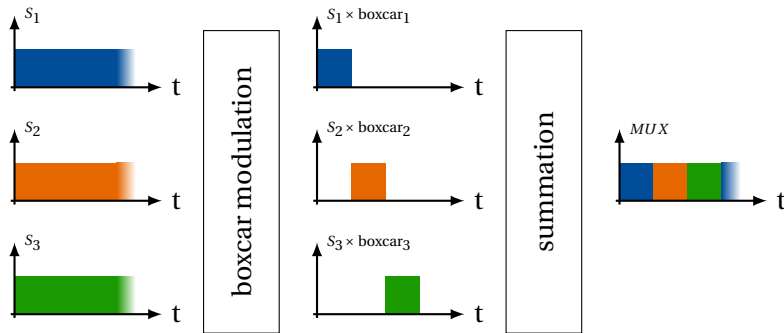


### Multiplexing $\Rightarrow$ spread spectrum

- ▶ 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**

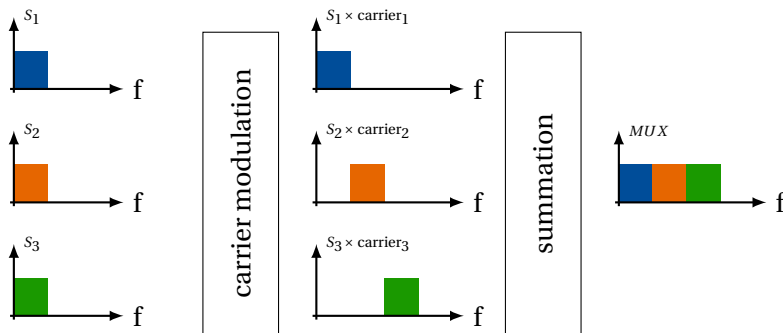


- ▶ Requires a specific boxcar (time shifted) modulation / signal
- ▶ *Limited duration*  $\equiv$  **sampling**

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

# Frequency Domain Multiplexing (FDM)

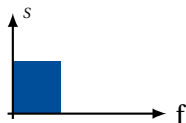
Frequency **transposition** of each input signal ( $S_x$ ) is **summed**



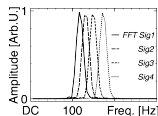
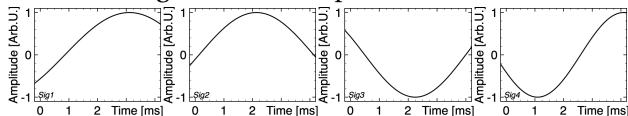
- ▶ Requires a specific frequency carrier / signal
- ▶ *Summation*  $\equiv$  increasing the **bandwidth** and the **dynamic**

# Sine waves multiplexing

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

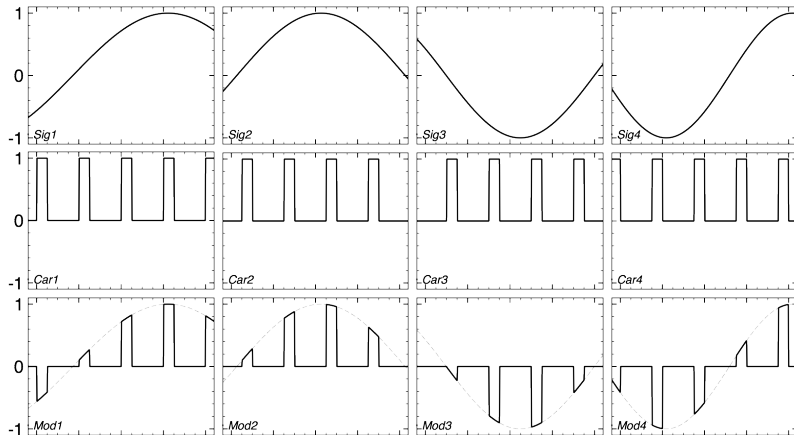


from now, signals will be represented as 4 sine waves



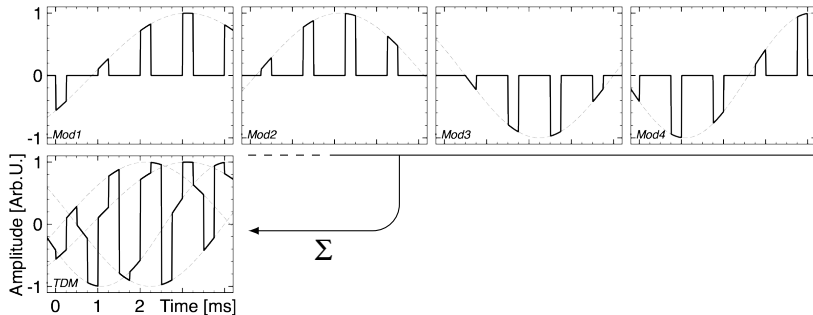
# Time Domain/Division Multiplexing - TDM

## Modulation - Sampling



# Time Domain/Division Multiplexing - TDM

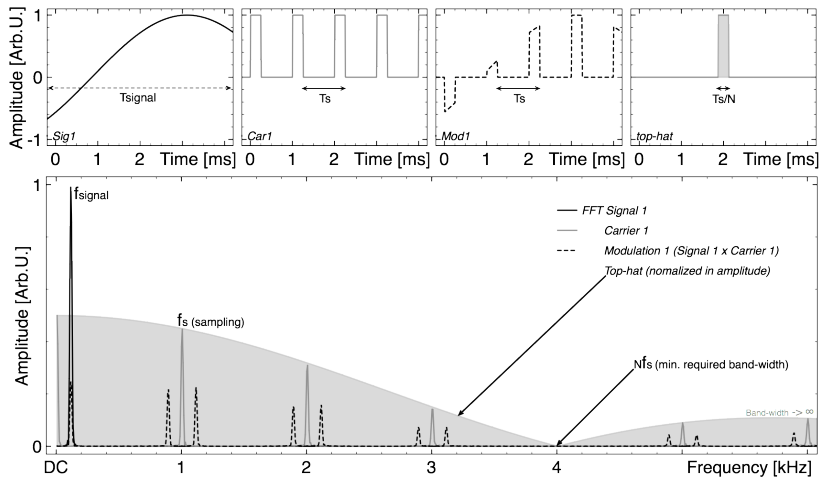
## Summation - multiplexing





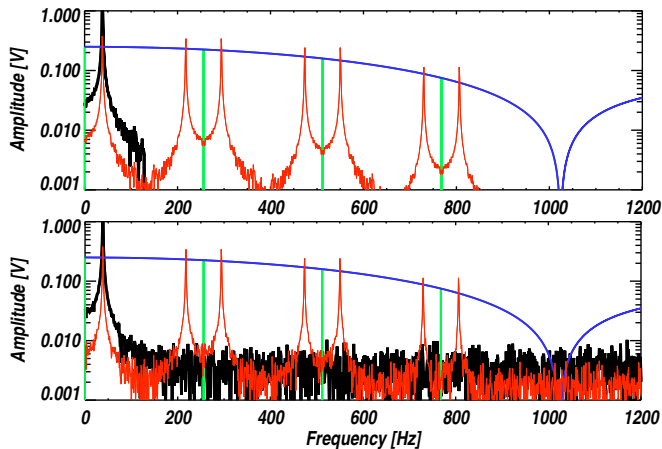
# Time Domain/Division Multiplexing - TDM

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



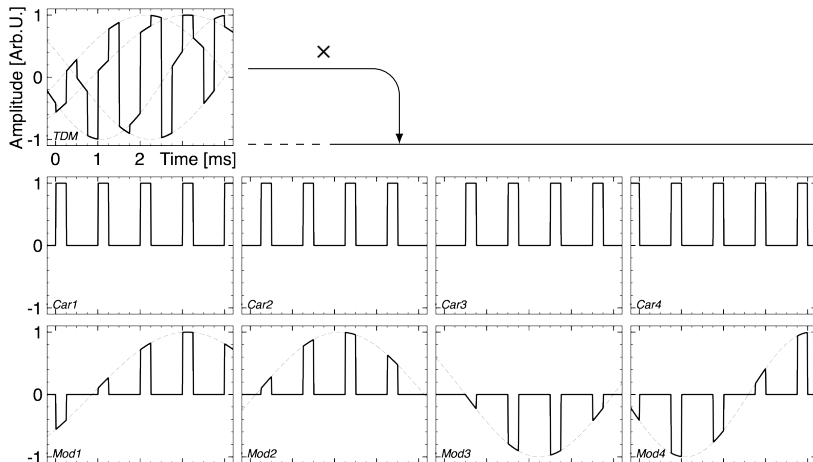
# Time Domain/Division Multiplexing - TDM

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



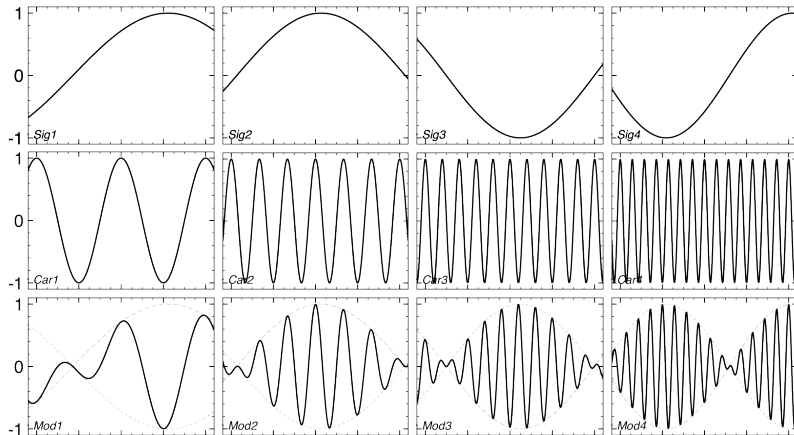
# Time Domain/Division Multiplexing - TDM

demultiplexing before sample & hold and filtering



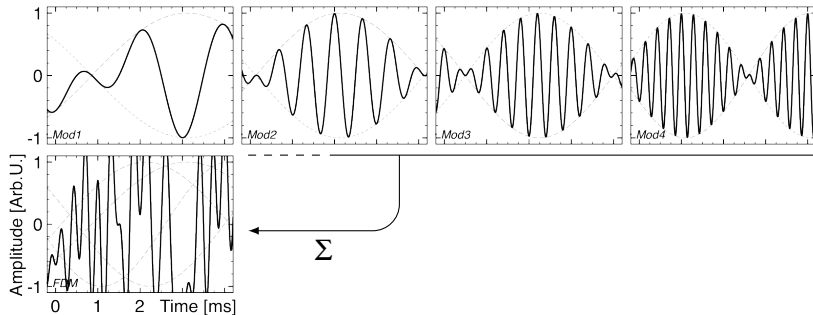
# Frequency Domain/Division Multiplexing - FDM

## Modulation - Frequency transposition



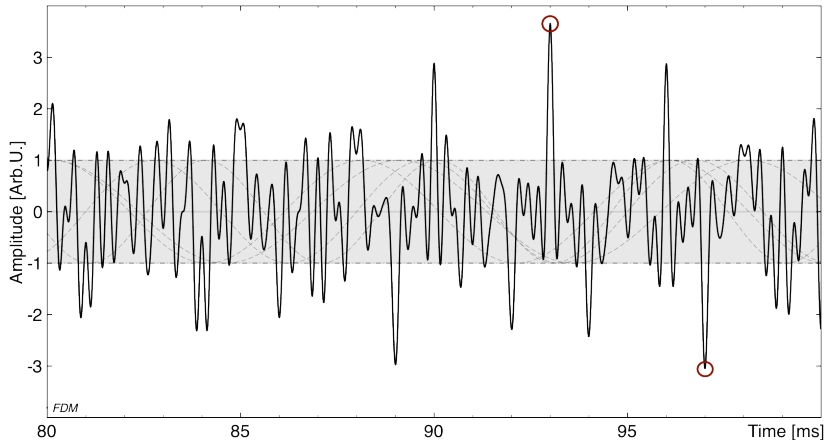
# Frequency Domain/Division Multiplexing - FDM

## Summation - multiplexing



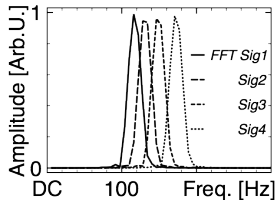
# Frequency Domain/Division Multiplexing - FDM

Increasing of the amplitude of the multiplexed signal

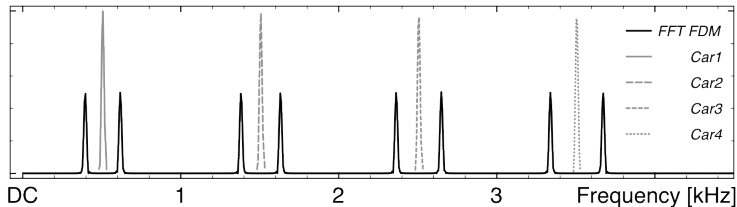


# Frequency Domain/Division Multiplexing - FDM

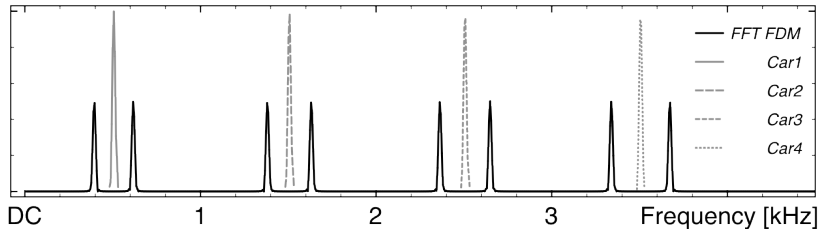
Spectrum occupancy :  $BW_{FDM} > 2 \times N \times BW_{Sig}$



Multiplexing



# Frequency Domain/Division Multiplexing - FDM



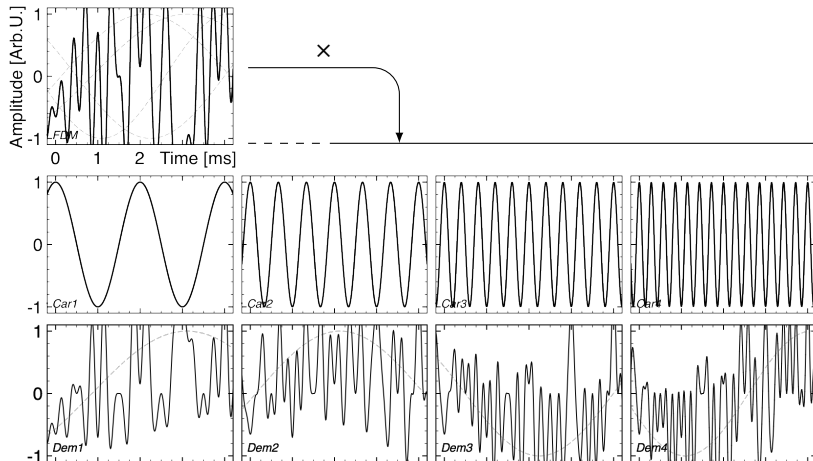
## Aliasing of the unfiltered signal and white noise

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



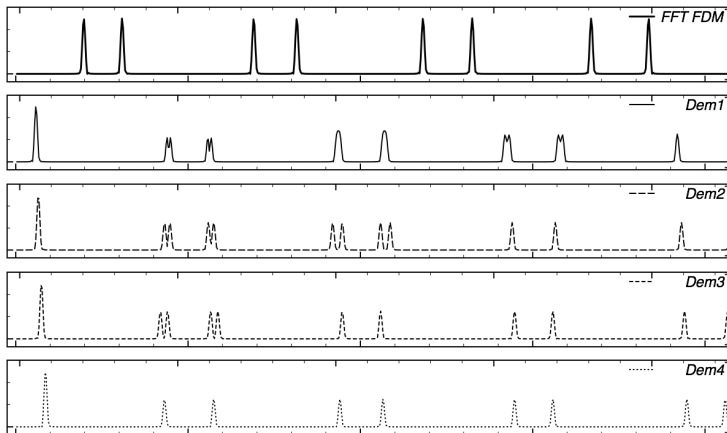
# Frequency Domain/Division Multiplexing - FDM

demultiplexing before filtering



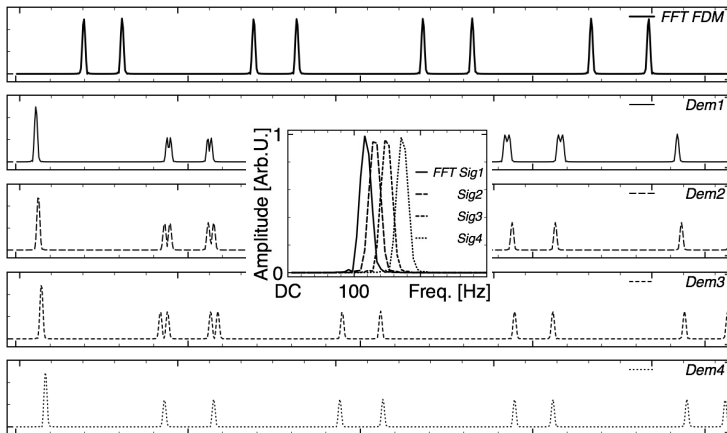
# Frequency Domain/Division Multiplexing - FDM

demultiplexing in the frequency domain



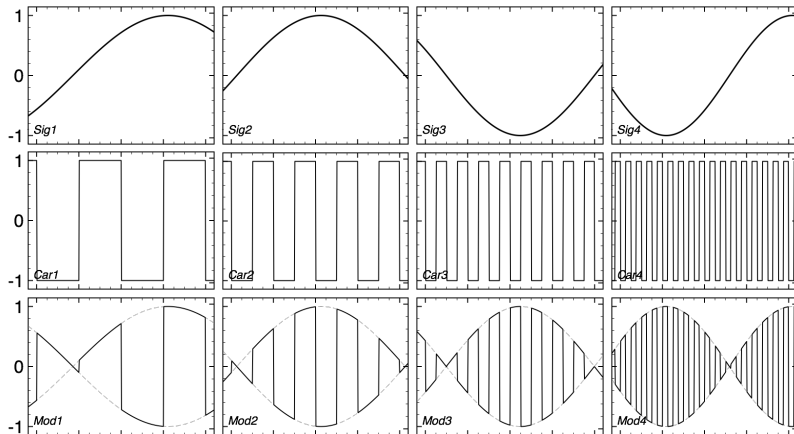
# Frequency Domain/Division Multiplexing - FDM

demultiplexing in the frequency domain



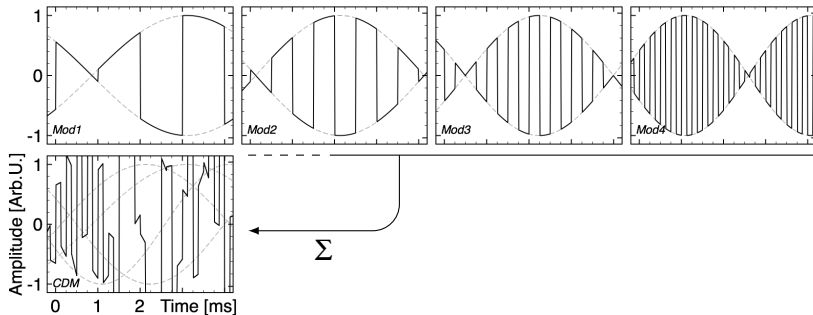
# Coded Domain/Division Multiplexing - CDM

Modulation - "Coding" (not the Walsh code)



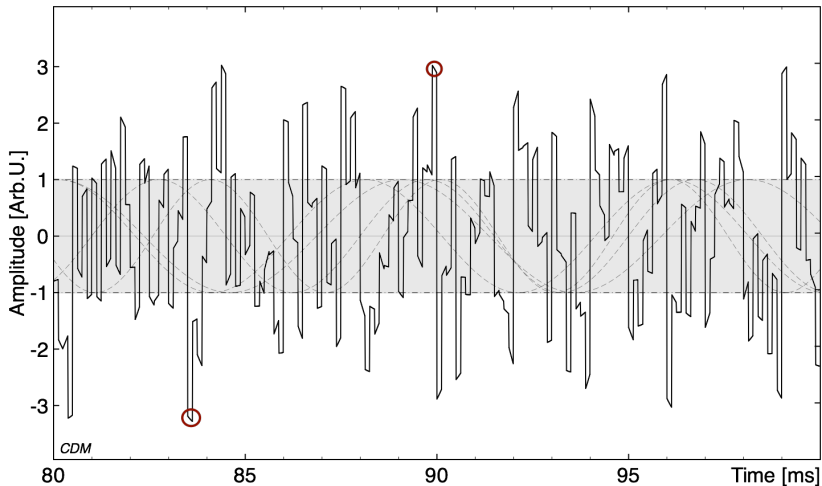
# Coded Domain/Division Multiplexing - CDM

## Summation - multiplexing



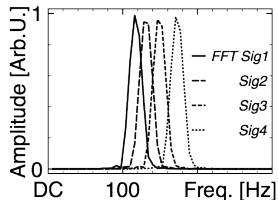
# Coded Domain/Division Multiplexing - CDM

Increasing of the amplitude of the multiplexed signal

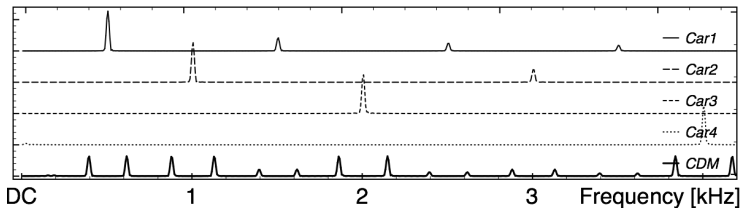


# Coded Domain/Division Multiplexing - CDM

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

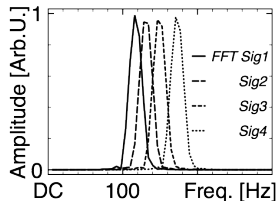


Multiplexing

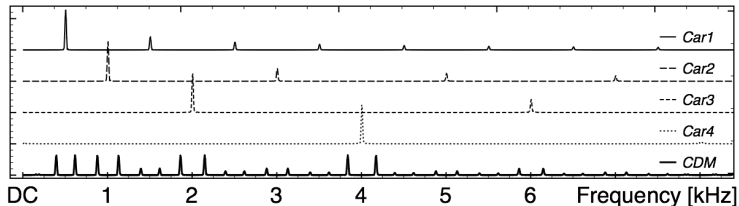


# Coded Domain/Division Multiplexing - CDM

Spectrum occupancy: wide "spread" spectrum



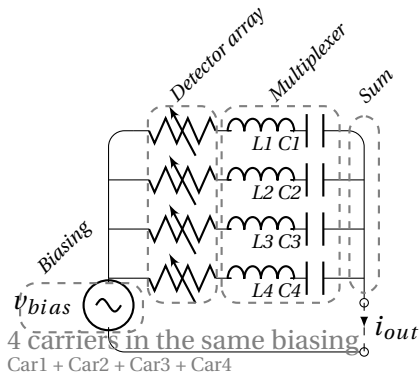
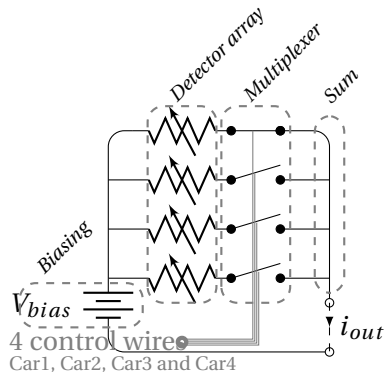
Multiplexing





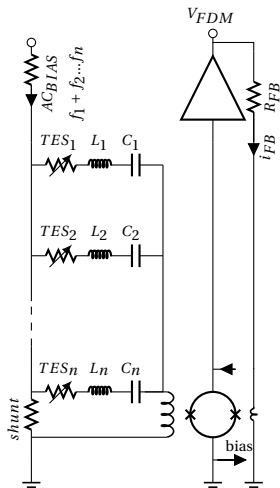
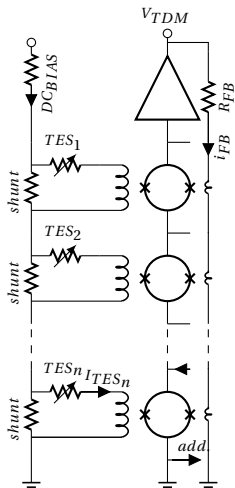
# TDM vs FDM principle

## Multiplexer 1D

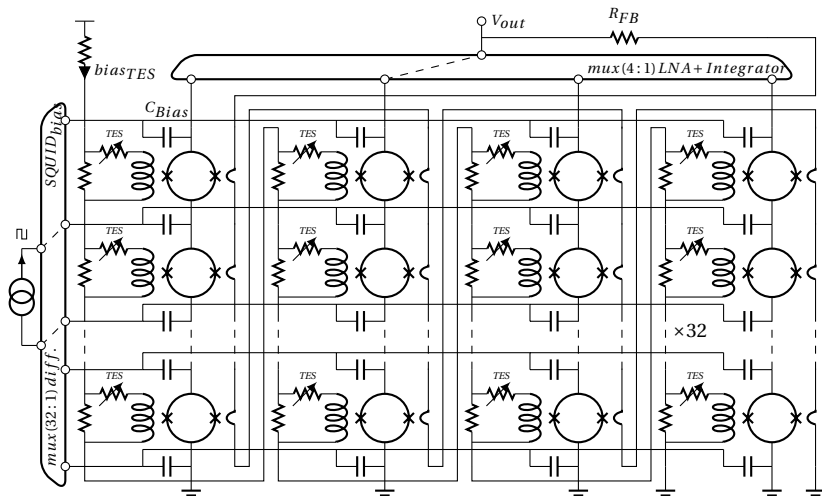


# TDM vs FDM with SQUID 1D

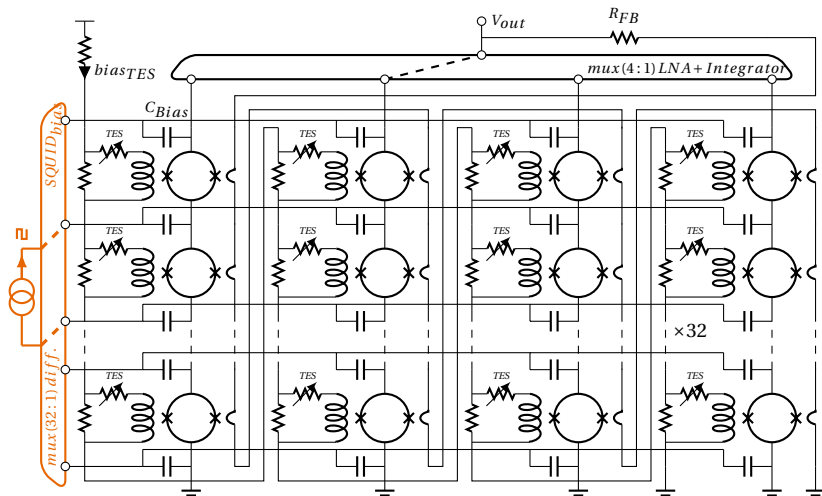
## Multiplexer 1D



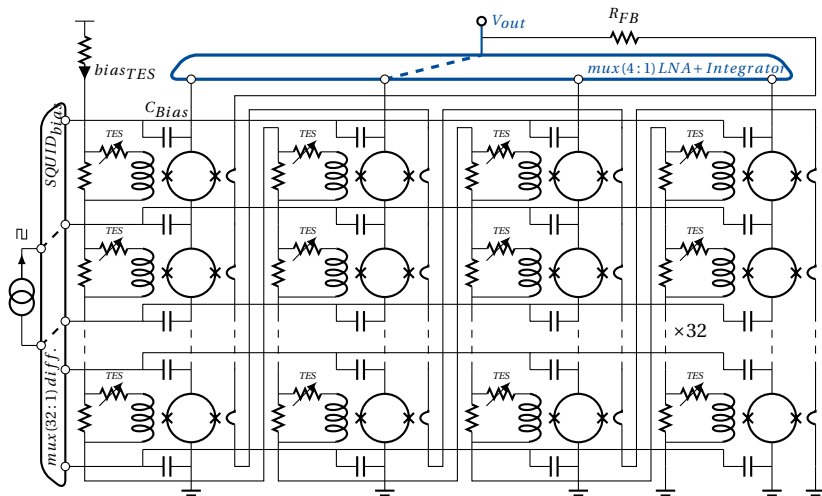
## Cryogenic TES time domain multiplexer - QUBIC



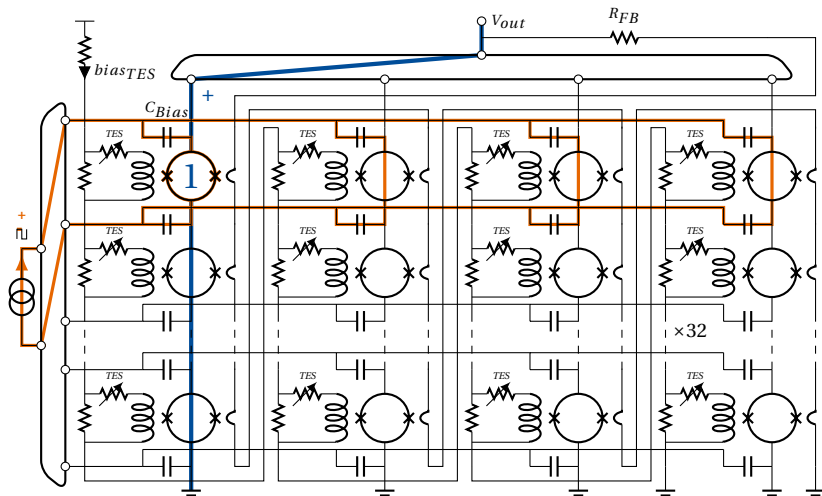
## Cryogenic TES time domain multiplexer - QUBIC



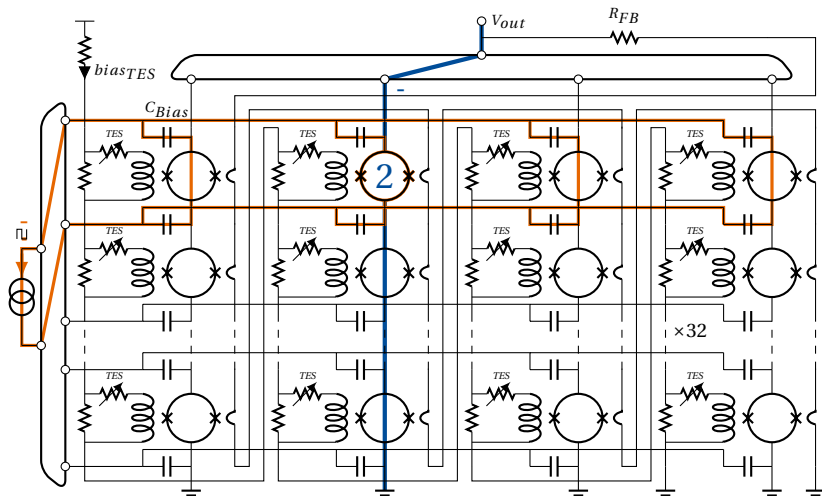
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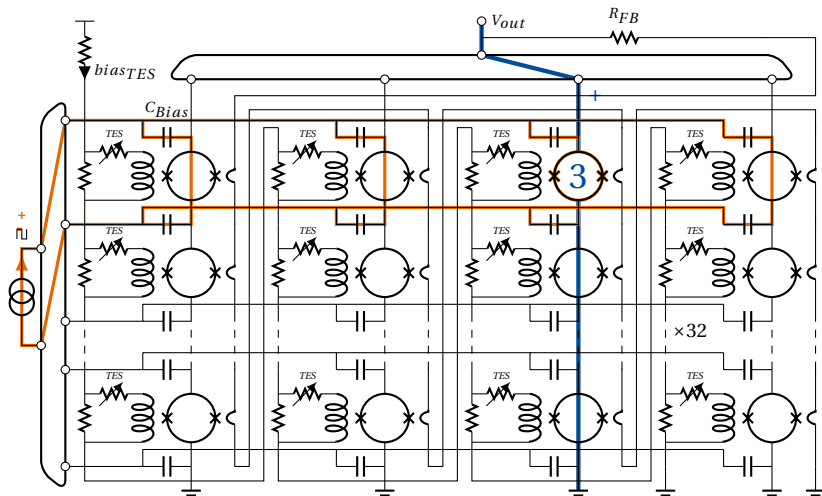
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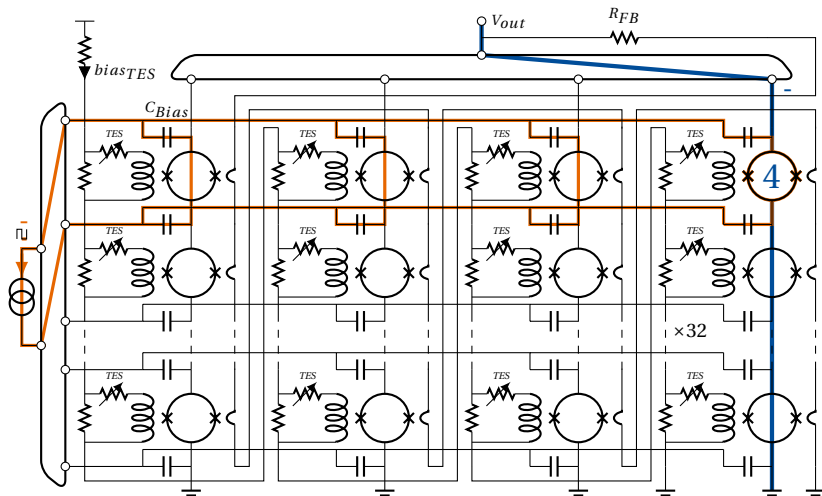


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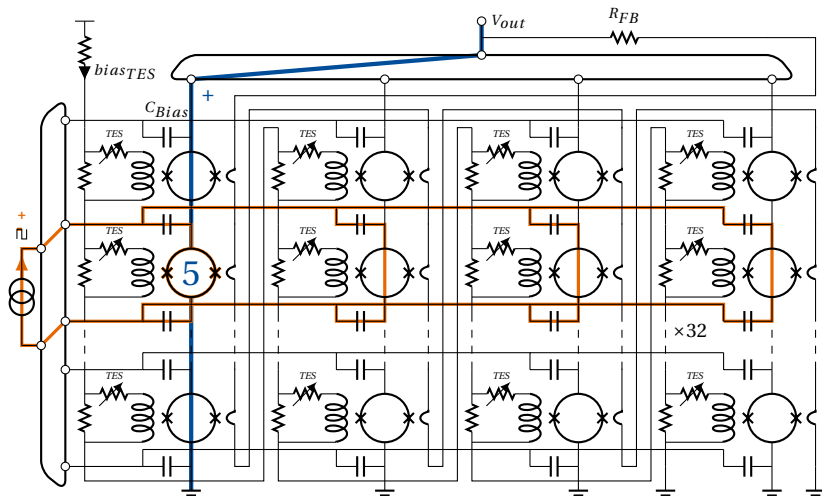




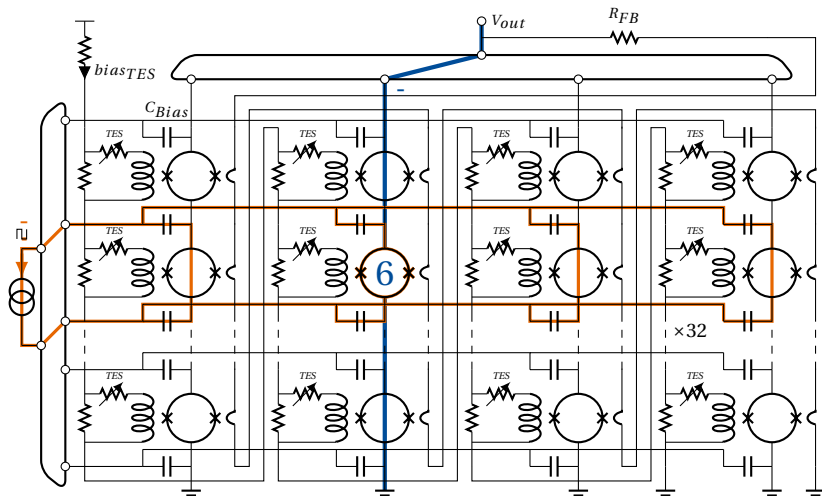
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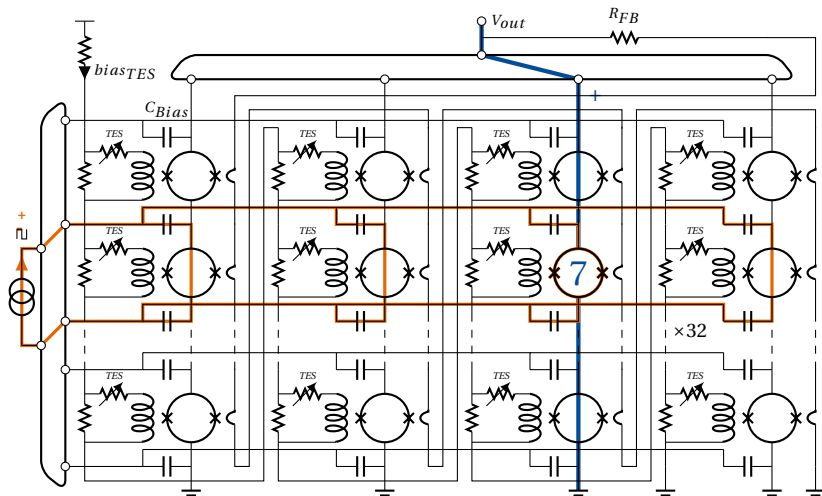
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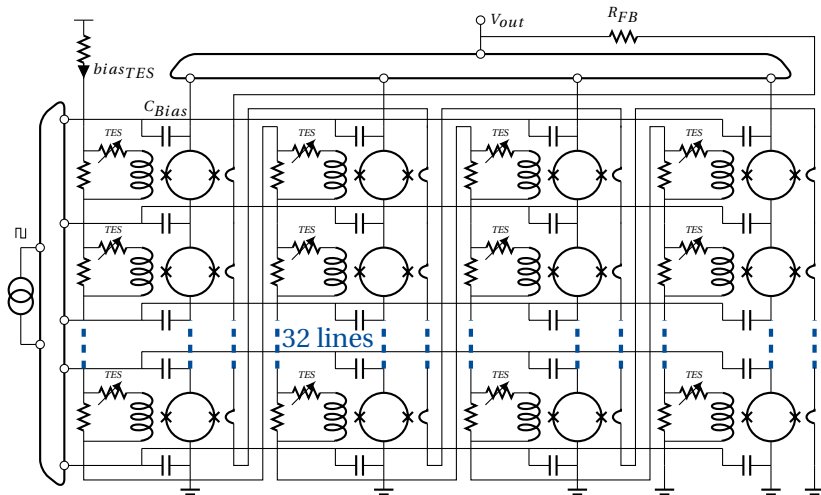


## Cryogenic TES time domain multiplexer - QUBIC

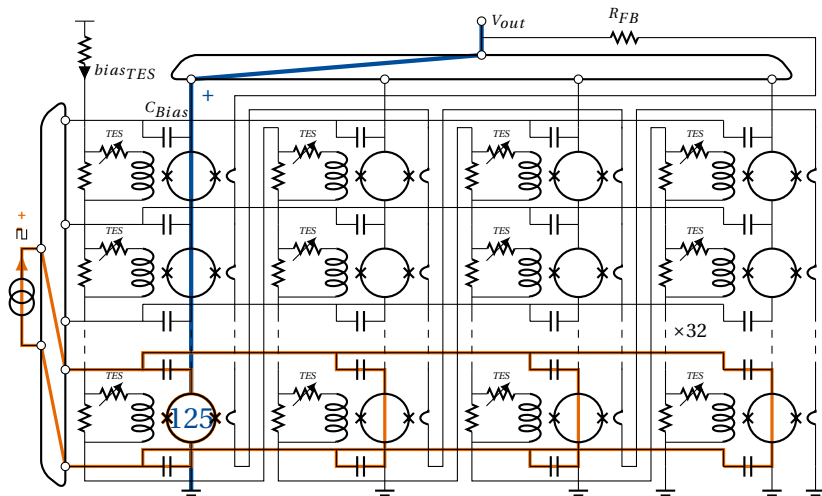




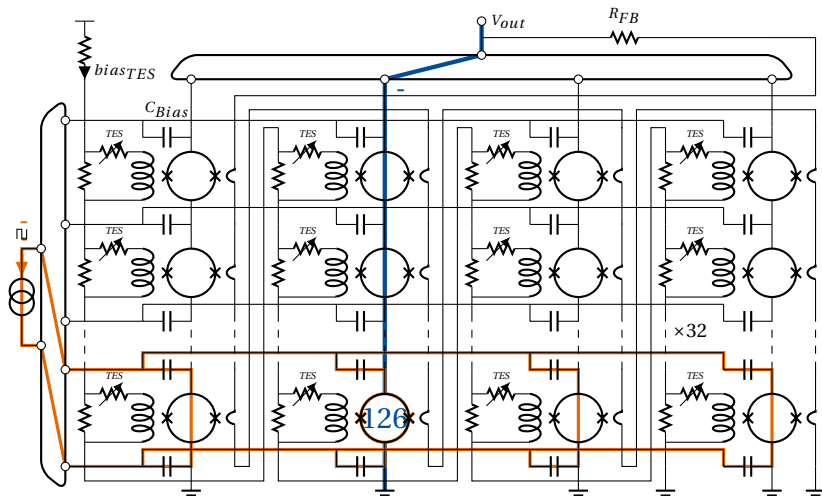
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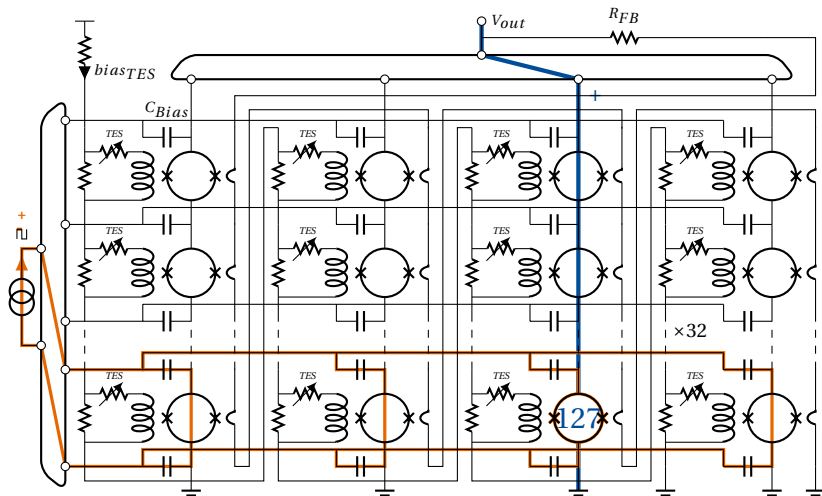


## Cryogenic TES time domain multiplexer - QUBIC

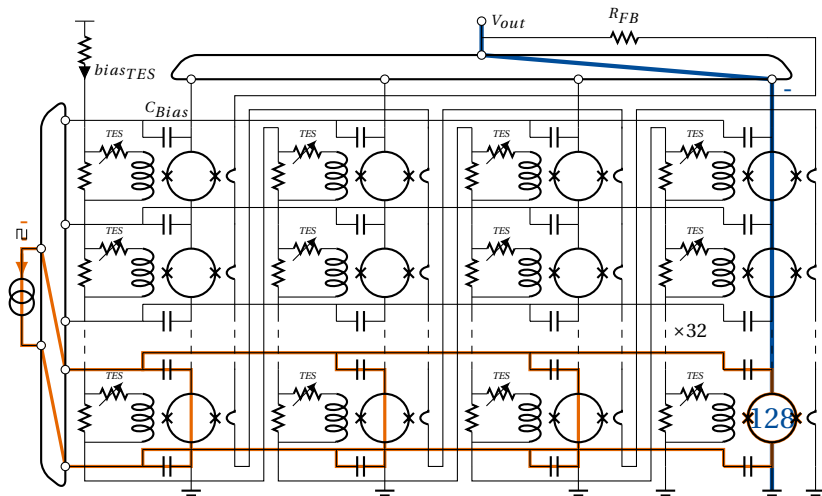




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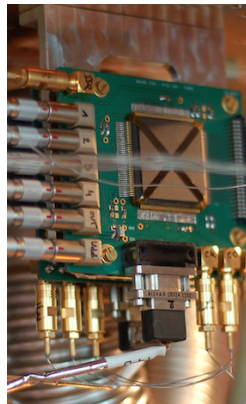
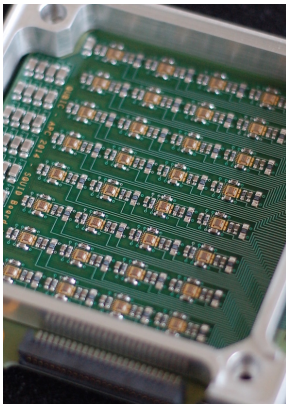
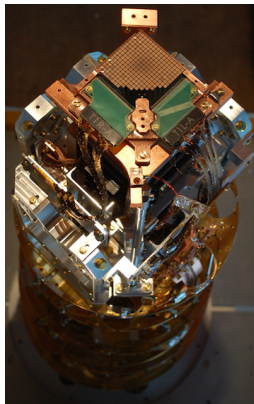


## Cryogenic TES time domain multiplexer - QUBIC



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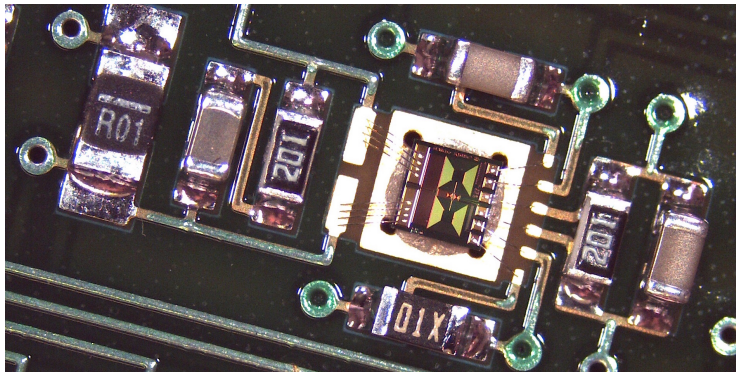
QUBIC readout chaîne : TES (300 mK) + SQUID (1K) + ASIC (77K)



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

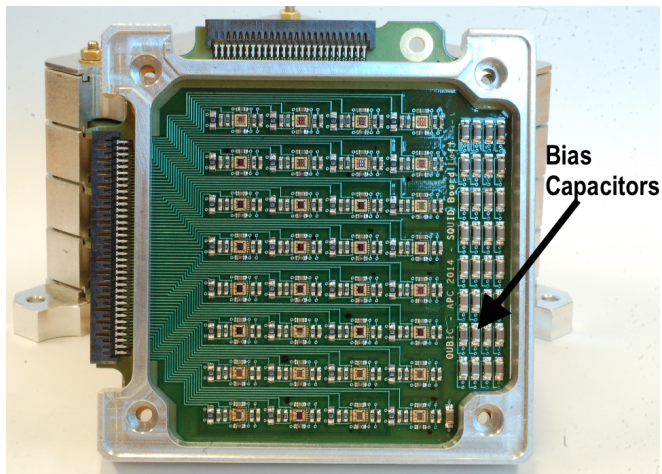
## SQUID glued and wire bonded on a PCB

StarCryoelectronics SQ680 specific design.

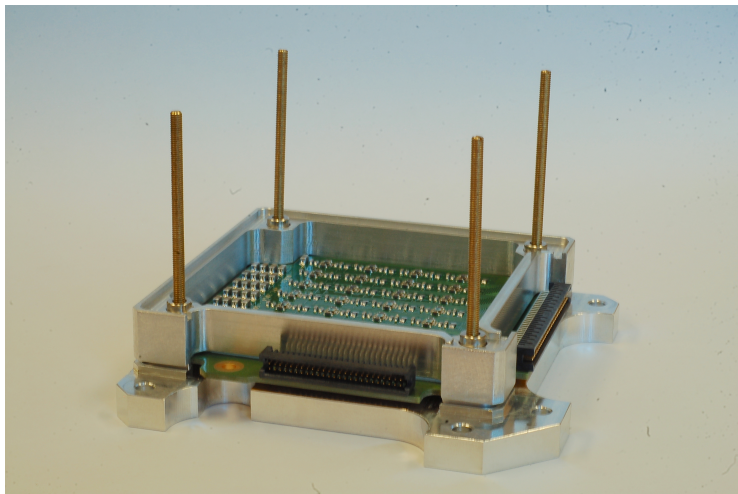


Solder plated track (no parasitic resistances)  
Shunt resistor and filter devices

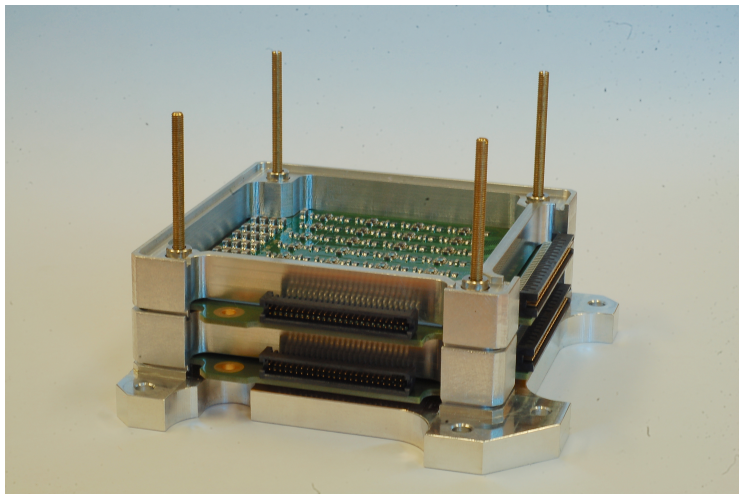
## 32 SQUIDs glued and wire bonded on a PCB



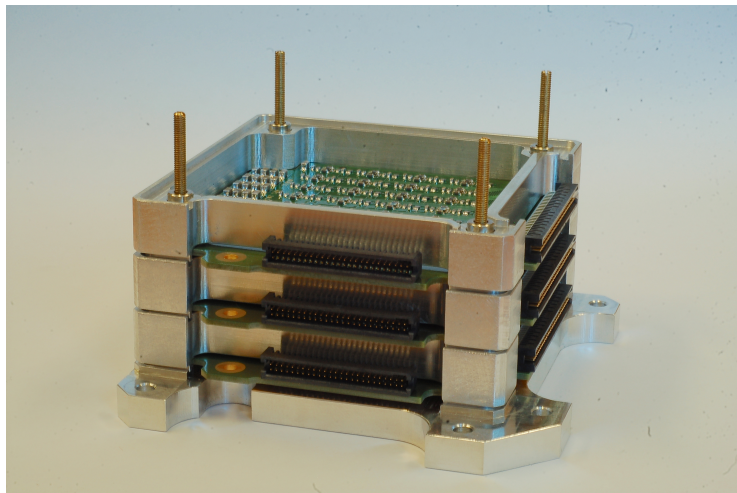
## 32 SQUIDs glued and wire bonded on a PCB



## 64 SQUIDs glued and wire bonded on a PCB

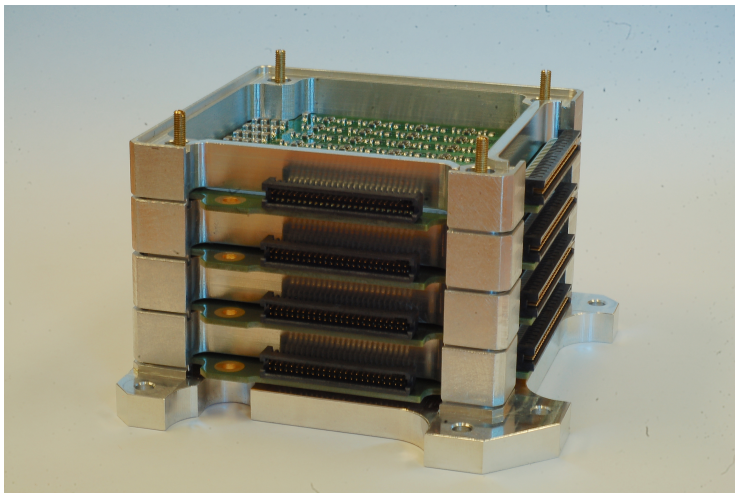


## 96 SQUIDs glued and wire bonded on a PCB

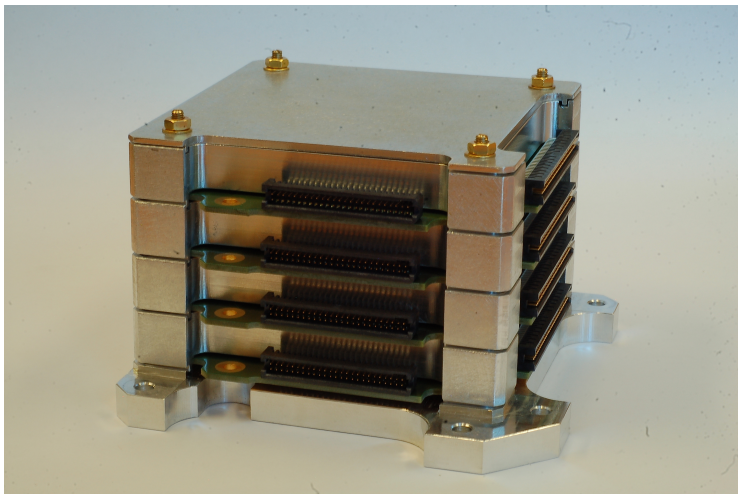




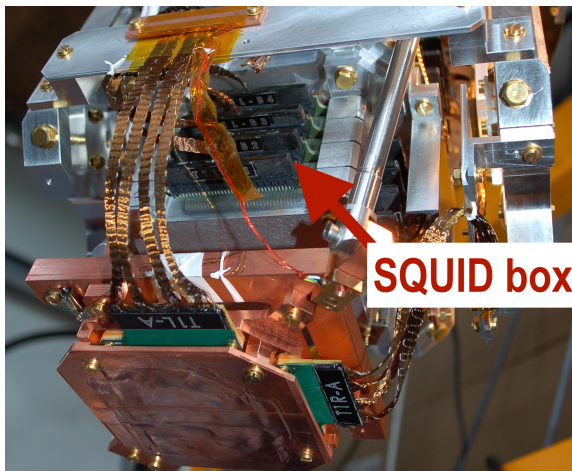
## 128 SQUIDs glued and wire bonded on a PCB



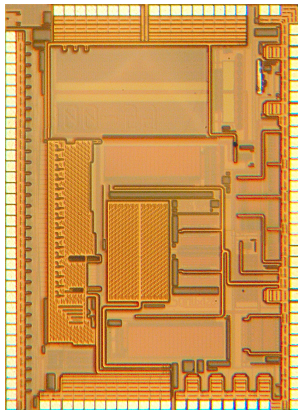
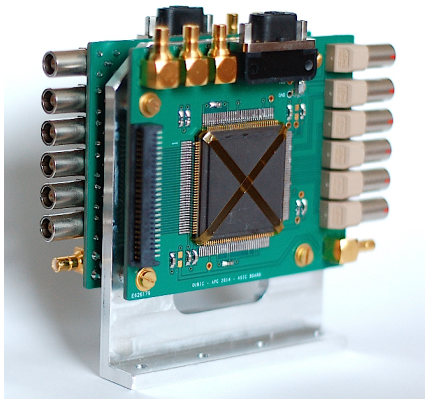
## 128 SQUIDs glued and wire bonded on a box



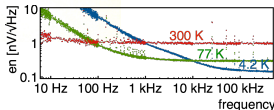
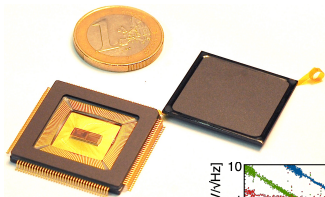
## SQUIDs glued and wire bonded on a box



# ASIC Stage (Application Specific Integrated Circuit)



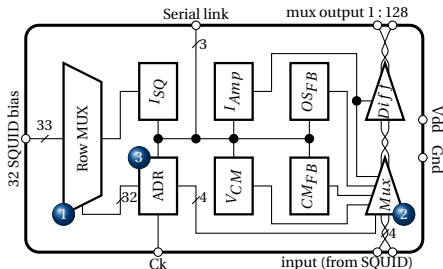
## SiGe ASIC for cryogenic 1:128 TD SQUID M



## BiCMOS SiGe ASIC

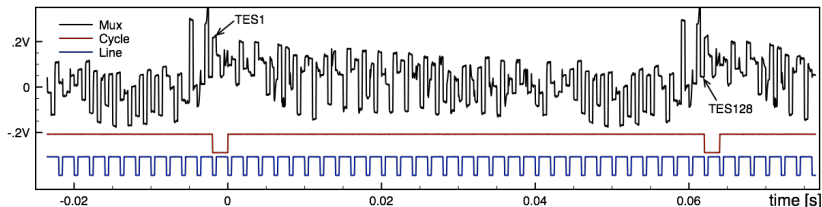
350nm AMS technology

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



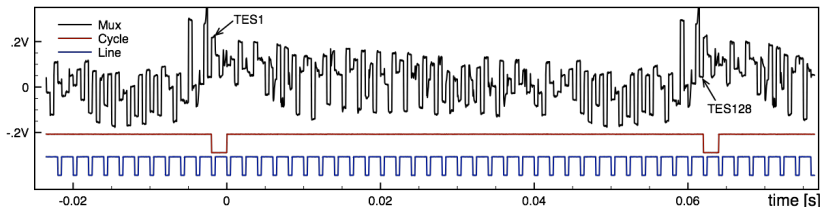
# Multiplexed time line

## 1:128 multiplexing rate

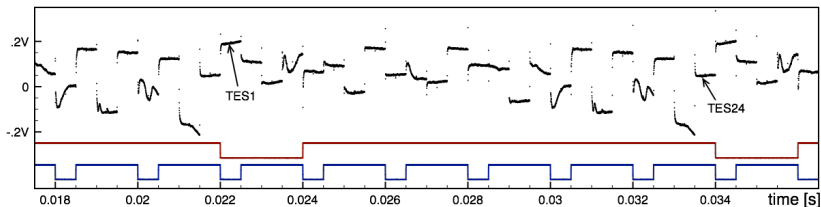


# Multiplexed time line

## 1:128 multiplexing rate



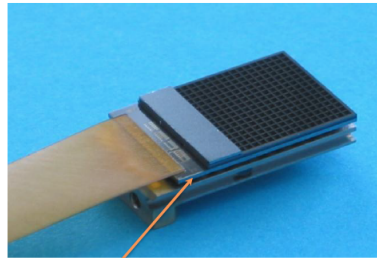
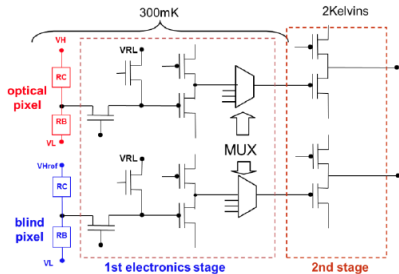
The ASIC allows to **reduce the part of the array readout**



## 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.

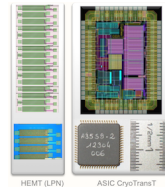
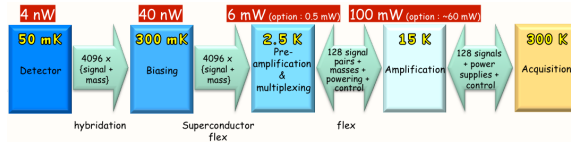
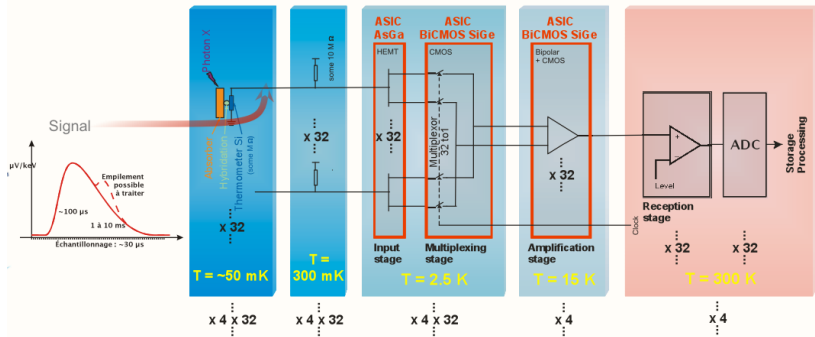


cold electronics layer

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



# Xray microcalorimeter + TDM (HEMT + SiGe)

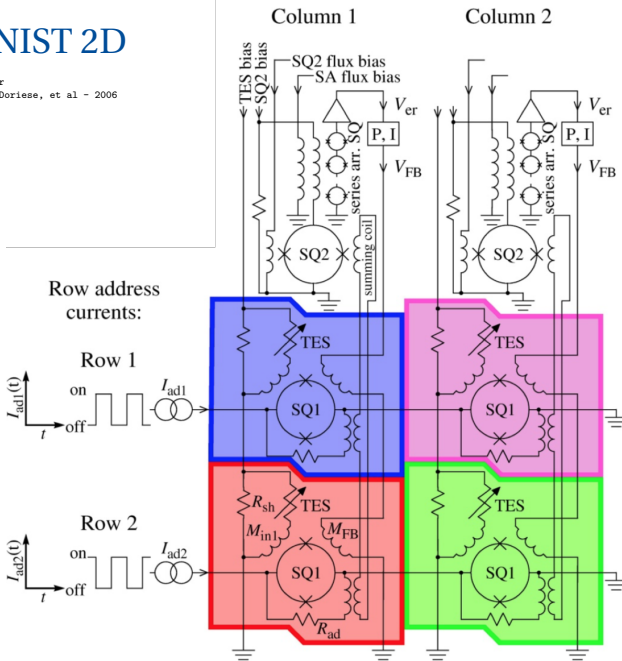


X. de la Broise et al. - CEA SEDI

# TDM by NIST 2D

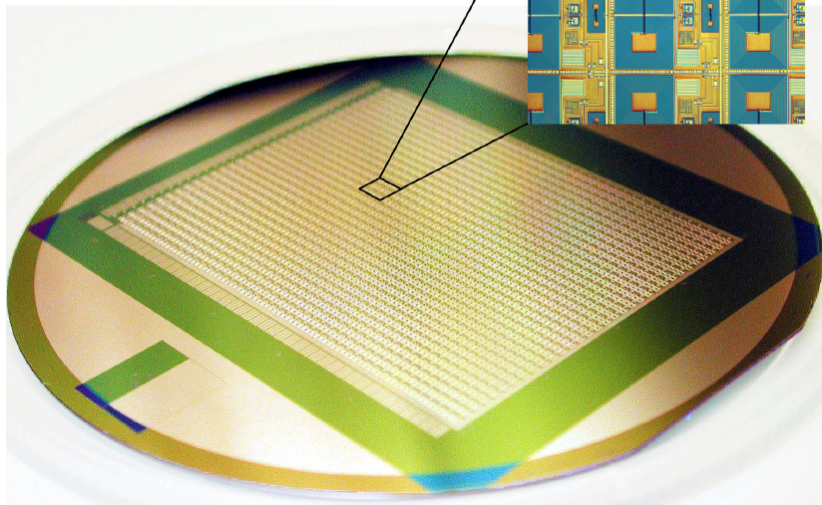
SQUID Multiplexer

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

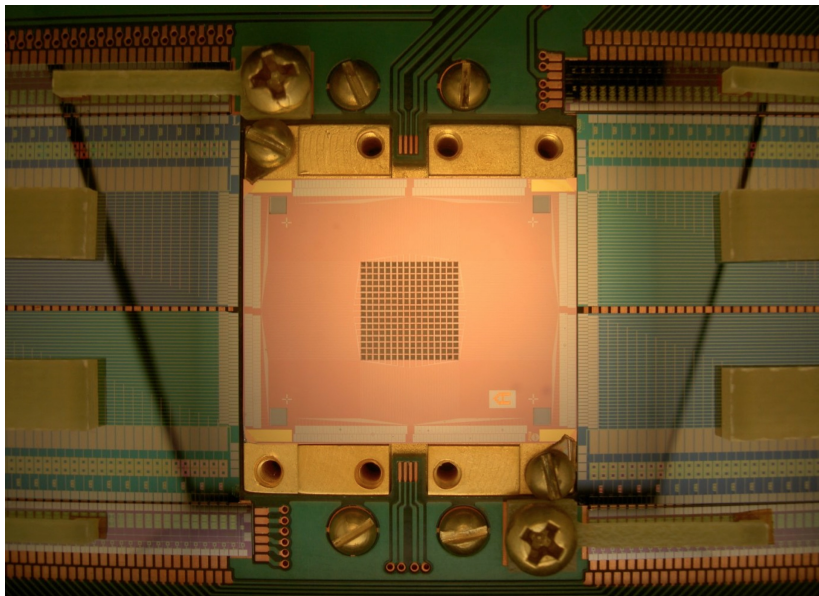


## TDM SCUBA2 SQUID Chip

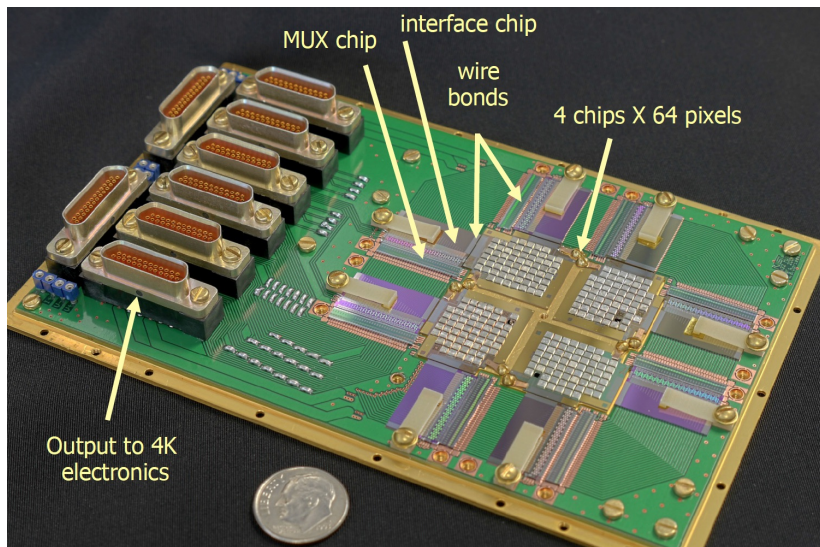
Wafer-scale processing assembled with indium bump-bonding on a TES array of 40x32 pixels



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

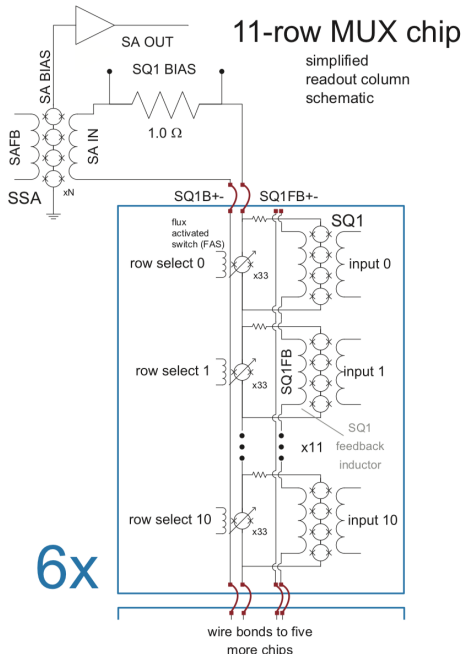


# TDM TES $\gamma$ -ray mux



# TDM with SQ1/FAS

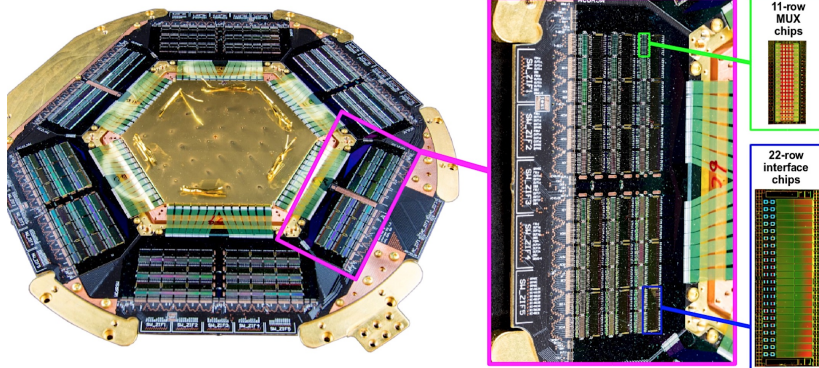
Readout of two-kilopixel TES arrays for Advanced ACTPol 32  
 Each SQ1 is shunted by a flux activated switch (FAS)



# TDM ACTpol Focal Plan

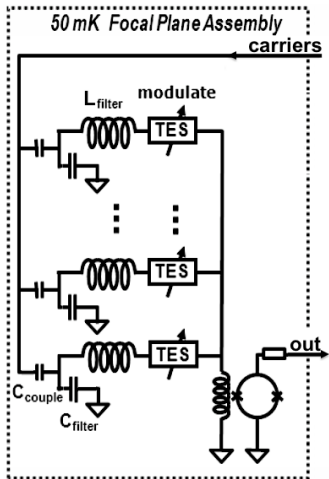
32 columns of 64 TESEs

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



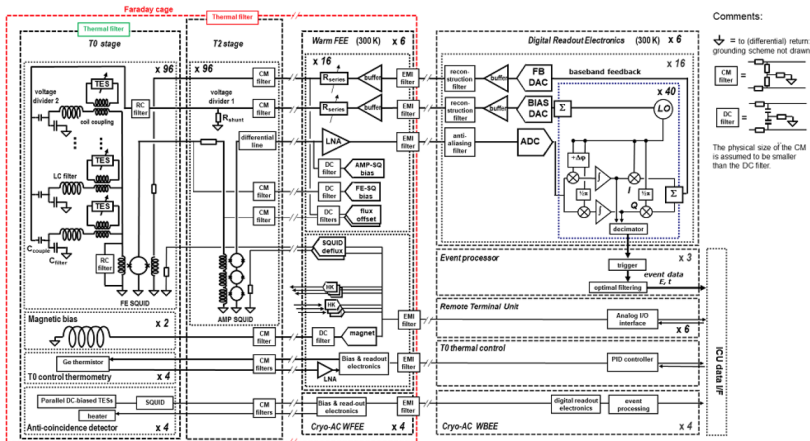
Readout of two-kilopixel transition-edge sensor arrays for Advanced ACTPol - S. W. Henderson et al.

# FDM by SRON 1D

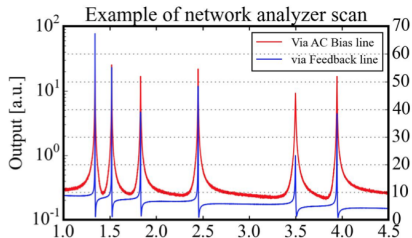
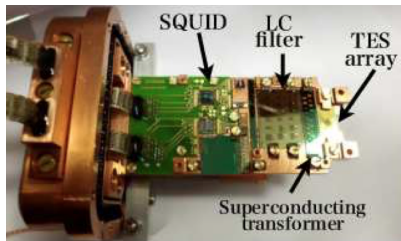




# FDM by SRON 1D with BaseBand FeedBack

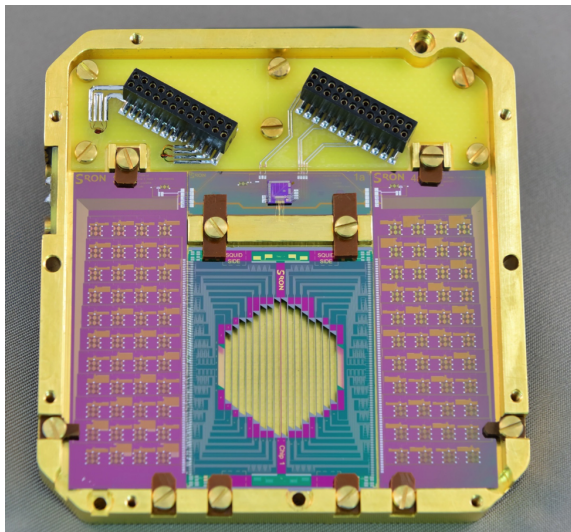


# FDM by SRON 1D ATHENA X-IFU demonstrator

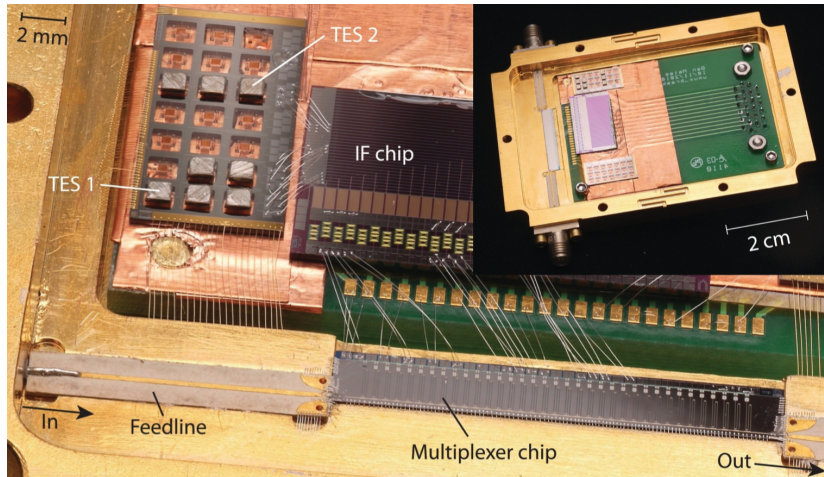


Development of FDM for the X-ray Integral Field Unit (X-IFU) on the Athena - H. Akamatsu et al.  
- 2016

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

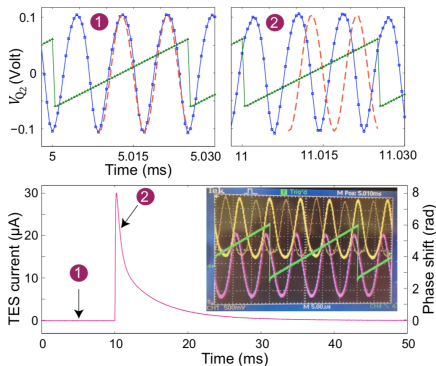
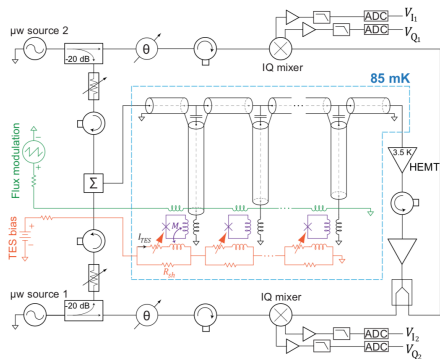


# Microwave SQUID multiplexing - NIST



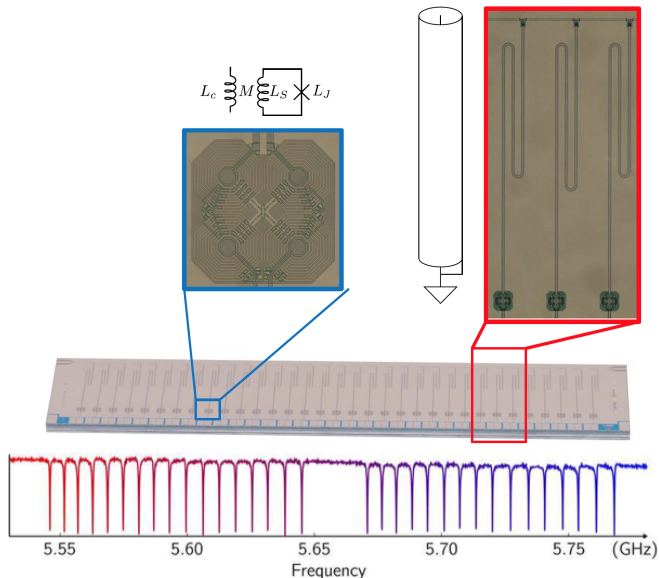
High-resolution gamma-ray spectroscopy with a microwave-multiplexed transition-edge sensor array

# Microwave SQUID multiplexing - NIST

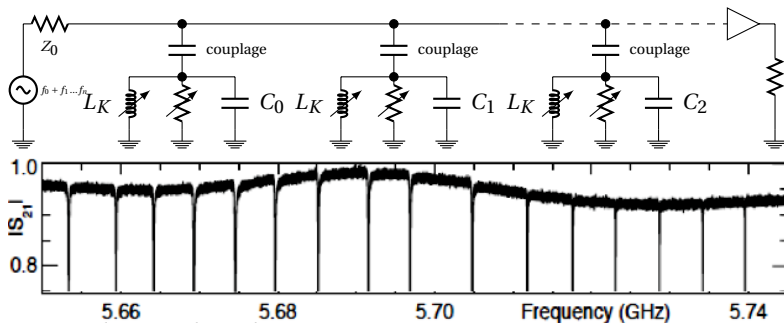


High-resolution gamma-ray spectroscopy with a microwave-multiplexed transition-edge sensor array  
*Multiplexing capability of MKIDs / DC biased - Irwin et al.*

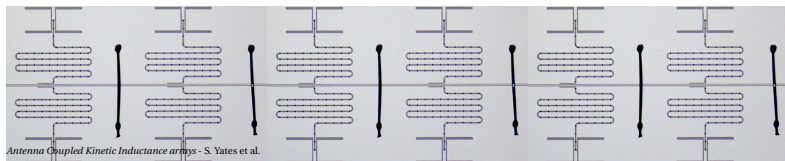
# Microwave SQUID multiplexing - NIST



## KID multiplexing

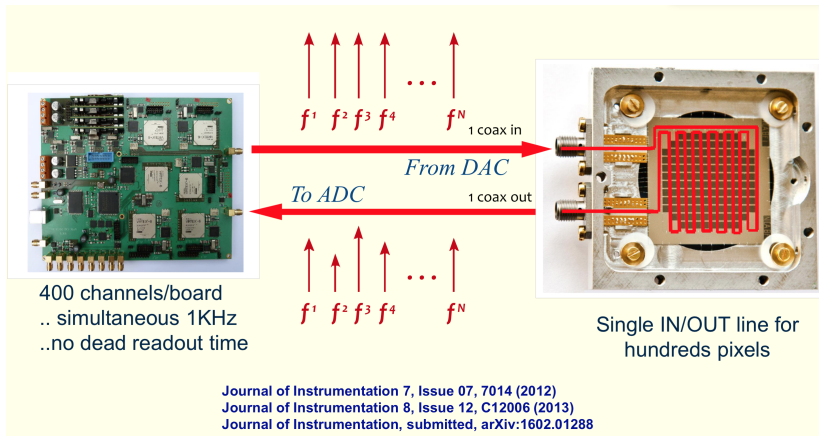


Microwave Kinetic Inductance Detectors: The First Decade - B. Mazin



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

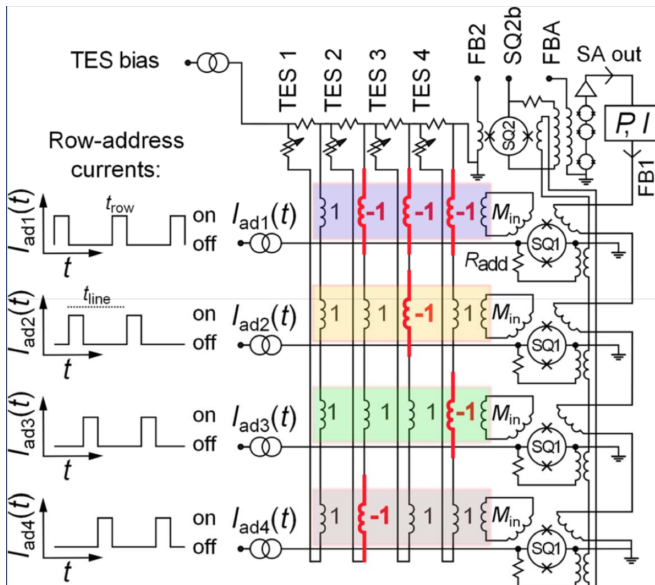
# KID/FDM by NEEL



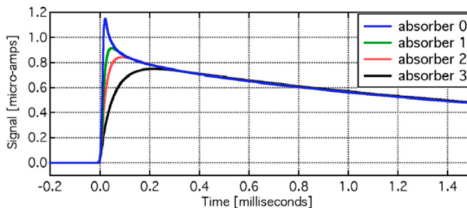
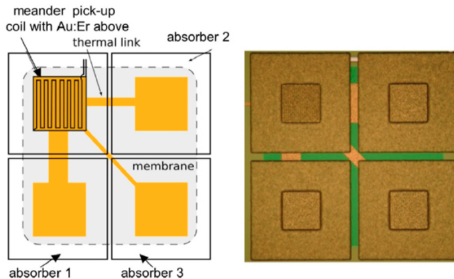
NIKA and NIKA2: from the pathfinder KID camera to the ultimate mm-wave imaging/polarimetry at the 30-meters Pico Veleta telescope - A. Monfardini - 2017



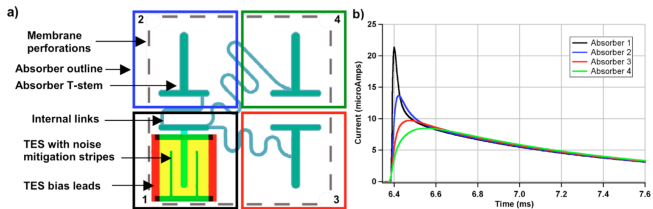
## CDM by NIST 1D



# 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 ...