Transition Edge Sensors

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Literature/Acknowledgement

- Acknowledgement to Christian Enns and Dan McCammon for making available lecture material on TES-micro-calorimeters
- Acknowledgement to Marcel Bruijn and Bob Dirks for making sheets on the production process and on device characterization available
- For literature please read:
  - Transition-Edge Sensor by Kent Irwin and Gene Hilton

    in Cryogenic Particle Detectors, Topics in Appl. Physics, Vol 99

    Editor: Christian Enns, Springer Verlag (2005)
  - Proceedings of Low Temperature Detector (LTD) conferences and references in there

Content TES physics

1) Schematic of Calorimeter Principle
2) Electro-thermal feedback
3) Basic Pixel Design
    1) Heat Capacity
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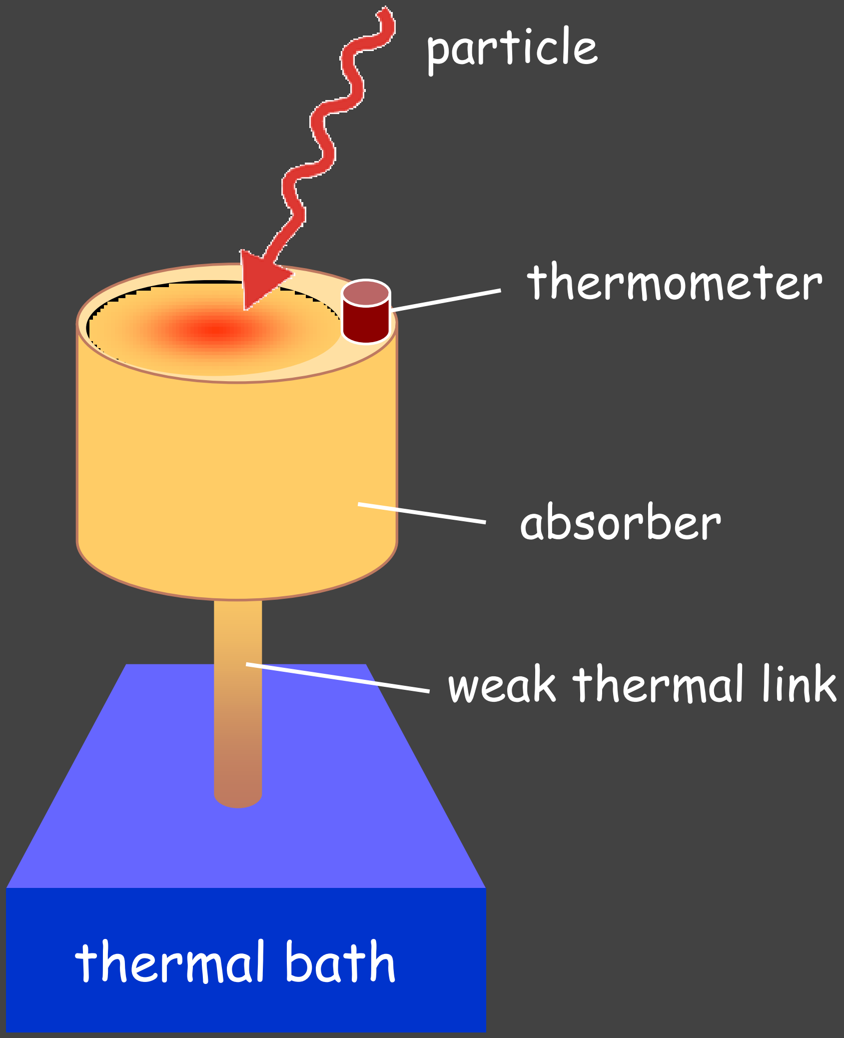
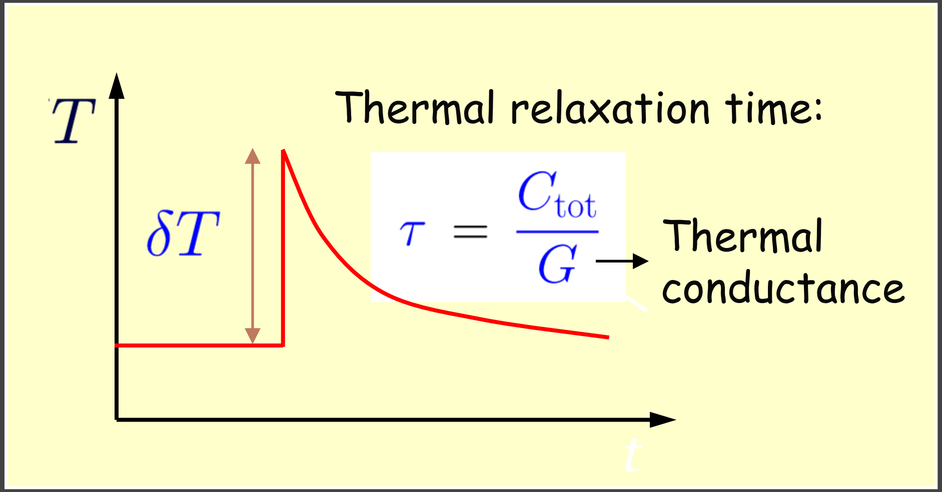
    3) TES-bolometer
4) Differential equations
    1) Linearization
    2) Matrix notation in frequency domain
    3) Responsivity
    4) Noise
    5) Complex impedance
5) Energy resolution
    1) Time domain
    2) Frequency domain
6) Pixel characterization (example)

Calorimeter Principle





Thermal relaxation time:

$$\tau = \frac{C_{\mathrm{tot}}}{G}$$

→ Thermal conductance

$$\delta T = \frac{E}{C_{\mathrm{tot}}}$$

C_{tot} : phonons

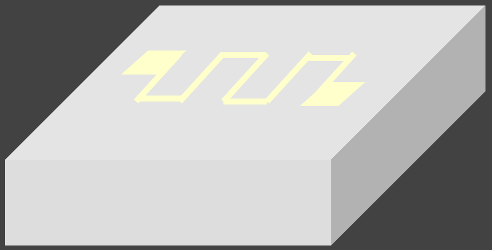
electrons

spins

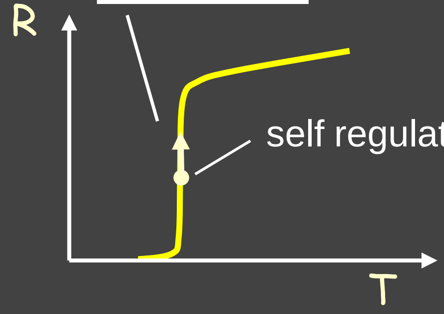
tunneling states

quasi particles

Superconducting Transition Edge Sensors (TES)



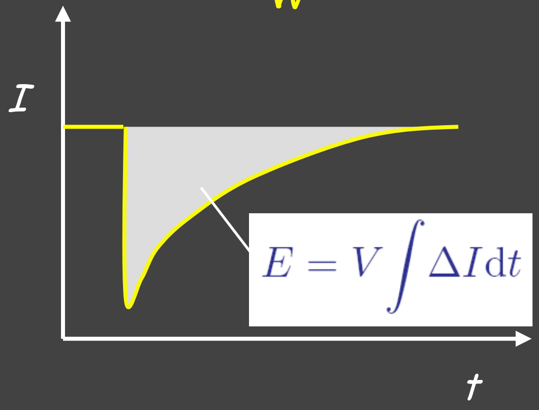
$$\alpha = \frac{\mathrm{d}\log R}{\mathrm{d}\log T}$$



self regulated working point

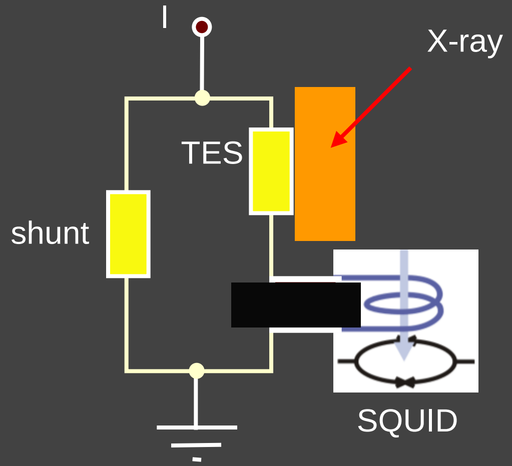
Materials

Mo/Cu
Mo/Au
Ir/Au
Ti/Au
W



$$E = V\int \Delta I \mathrm{d}t$$

Electro-thermal feedback



K. D. Irwin, Appl. Phys. Lett. **66**, 1945 (1995)

heat input:

→ R_{TES} goes up

→ joule heating decreases

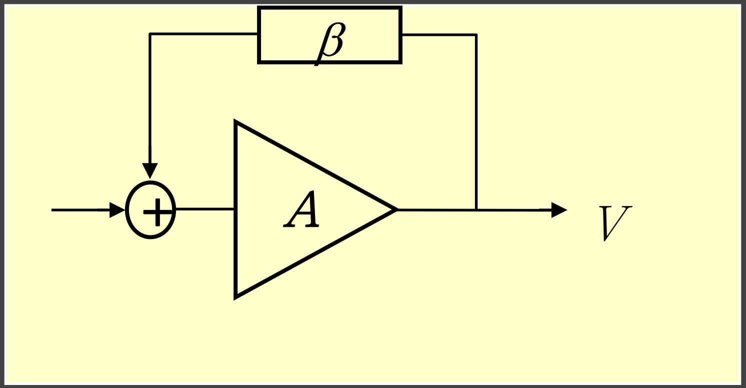
fast response time

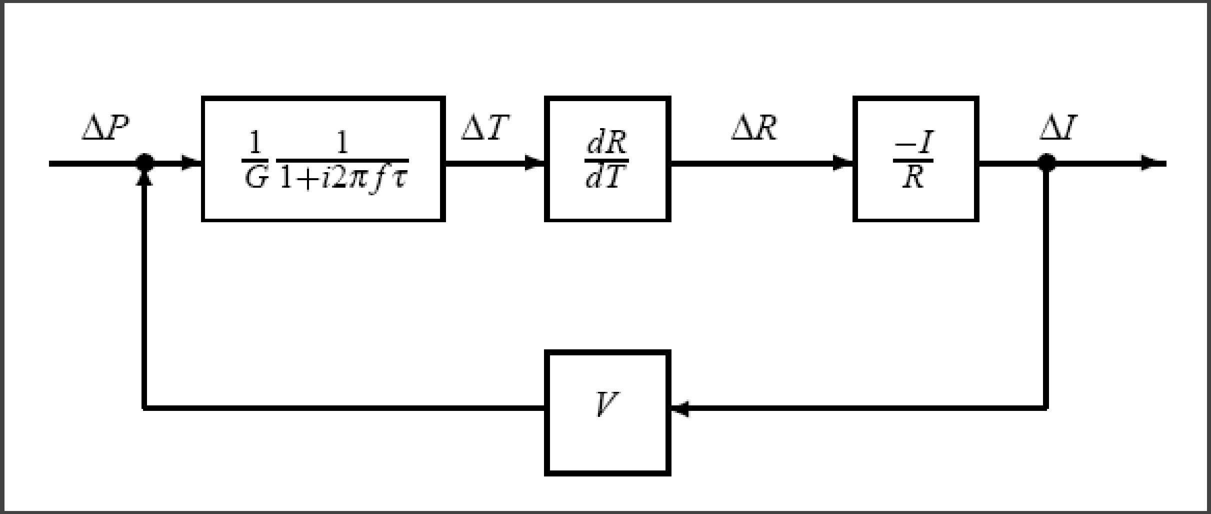
$$\tau_{\mathrm{eff}} = \frac{\tau}{1 + \alpha/n}$$

$$G \propto T^{n-1}$$

Electro-thermal Feedback

$$S = \frac{V_{out}}{V_{in}} = \frac{1}{\beta}\frac{A\beta}{1+A\beta}$$





$$L = \frac{1}{G}\frac{R\alpha}{T}\frac{-I}{R}\frac{V}{1+\omega\tau} = -\frac{\alpha P}{GT}\frac{1}{1+\omega\tau} = \frac{L_0}{1+\omega\tau}$$

$$S_I \equiv \frac{dI}{dP} = \frac{1}{V}\frac{L}{1+L} = \frac{1}{V}\frac{L_0}{1+L_0}\frac{1}{1+\omega\tau/(1+L_0)}$$

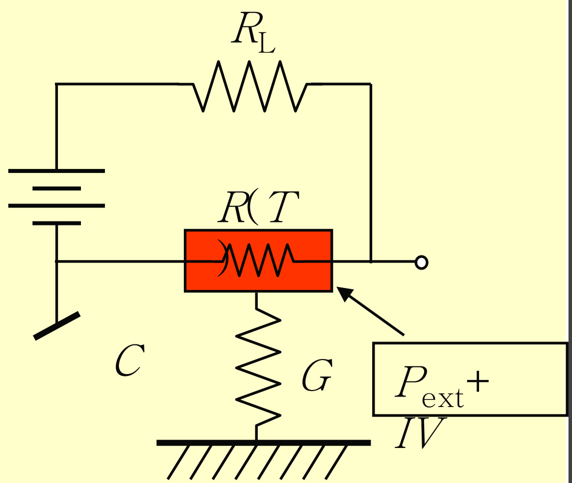
Open loop gain

$$L_0 = \alpha P / GT$$

$$P = K(T^n - T_0^n)$$

$$G = nKT^{n-1}$$

$$L_0 = \frac{\alpha}{n}[1 - \left(\frac{T}{T_0}\right)^n] \approx \alpha / n$$

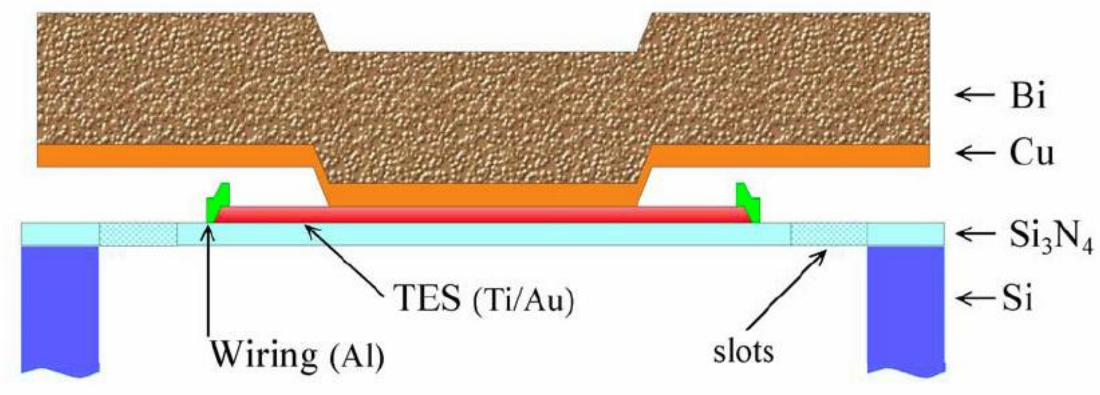


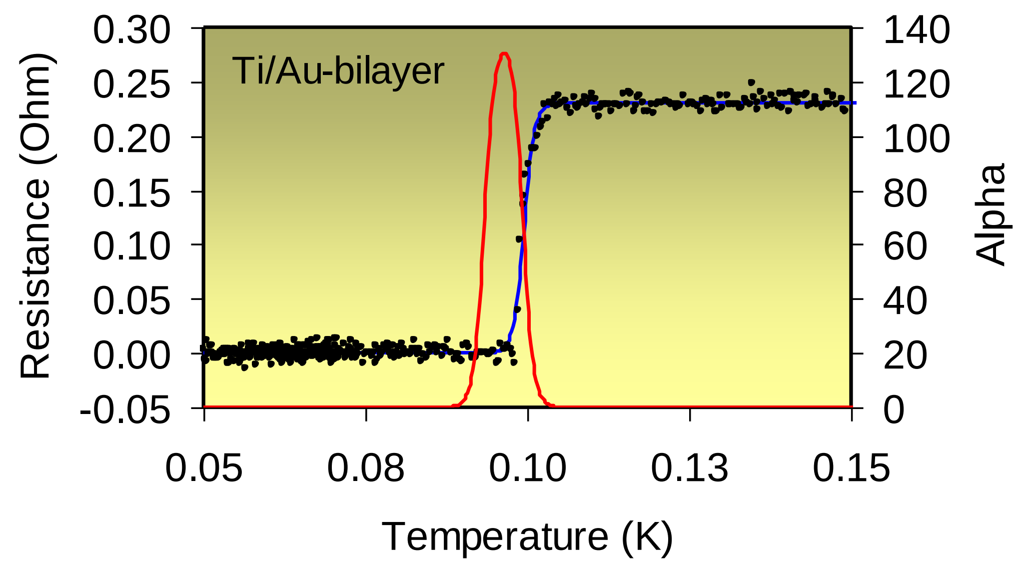
$$F_L = \frac{R - R_L}{R + R_L}$$

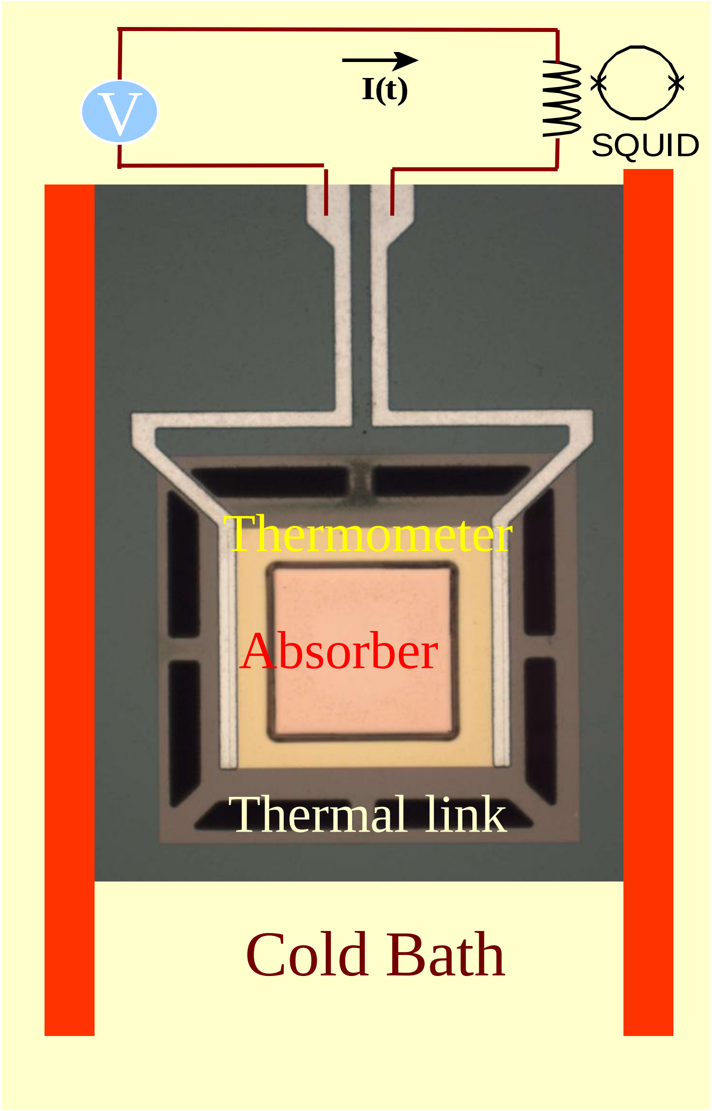
Influence load resistor
$L = L.F_L$

TES-based Micro-Calorimeter

BASIC PIXEL DESIGN







Typical Design parameters

- Heat Capacity
  - Electronic heat capacity $C = \gamma.T.V$ (γ the Sommerfeld parameter)
  - Phonon heat capacity $C = A.T^3.V$
  - For $T < 1$ K the C of normal metals is dominated by the electronic heat capacity (not for Bi)

Typical heat capacity of one pixel at T = 100 mK:

- TES 150 x 150 μm of 25nm Ti ($\gamma = 315$) and 50 nm Au ($\gamma = 71$). An area of 100 x 100 μm² under stem is normal (N), the S-rim is biased at $R/R_n = 0.2$. C superconductor phase = 2.43x that of normal phase — $C_{TES} = 7\ 10^{-14}$ J/K
- Cu-conductor 250 x 250 μm of 0.3 μm ($\gamma = 97$) — $C_{cu} = 1.8\ 10^{-13}$ J/K
- Bi-absorber 250 x 250 μm of 3 μm ($\gamma = 3.9$??) — $C_{BI} = 7.3\ 10^{-14}$ J/K
- SiN-membrane (220 x 180 x 1 μm) — $C_{SIN} \approx 1\ 10^{-13}$ J/K

Total heat capacity/pixel — **$C_{totaal} = 0.42$ pJ/K**

$E_{MAX} = C.\delta T \approx CT/\alpha$ For $\alpha \approx T/\delta T \approx 100$ we get $E_{MAX} \approx 2.6$ keV

Typical Design Parameters for heat transport

- Design of Heat Conductance value
  - Given typical electro-thermal feedback loop gains of 20x (eff. $\alpha = 100$)
  - Design a pixel with an effective time constant of 100 μs
  - → $C/G = 2$ ms or → $G \approx 2.5\ 10^{-10}$ W/K

- Heat transport
  - Generation of heat in electrical system of TES/absorber
  - Heat transport to bath by phonon’s in membrane:

1) e-ph coupling in TES/absorber $G_{e\text{-}ph} = n.\Sigma.VT^{n-1}$ with $n = 5$ and $\Sigma = 2\ 10^{9}$ $W/K^{5}m^{3}$. So → $G_{e\text{-}ph} \approx 2\ 10^{-7}$ W/K

2) Kapitza coupling to membrane $G_{kapitza} = n.\alpha_{K}.A.T^{n-1}$ with $n = 4$. Typically $\alpha_{K} = 125$ $W/K^{4}m^{2}$. So $G_{kapitza} = 1.12\ 10^{-8}$ W/K

3) Radiative phonon transport (Hoevers et al. Appl.Phys.Lett 86, 251903 (2005)) $G_{memb} = \xi.\sigma_{B}.n.A_{ph}.T^{n-1}$ $W/K^{3}m^{2}$ with $n = 4$. Typically $\xi = 0.78$. The Stefan-Boltzmann constant for phonon transport equals $\sigma_{B} = 157$ $W/K^{4}m^{2}$. So for $A_{ph} = 4 \times 150 \times 1$ μm² → $G_{memb} = 2.9\ 10^{-10}$ W/K
Reduction of this value is possible by structuring the SiN-membrane.
Typical $P \approx TG/n = 6$ pW

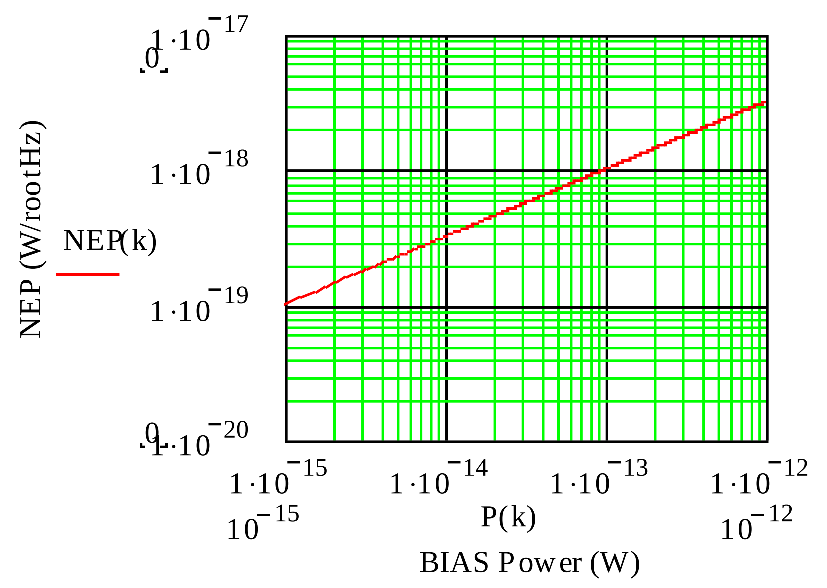
TES-Bolometer characteristics

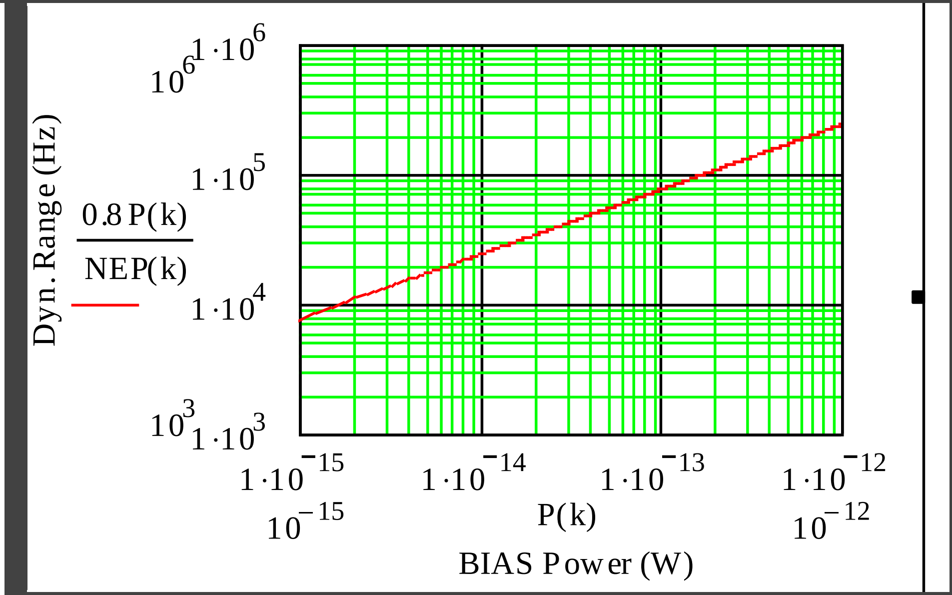
- NEP and Dynamic Range

$$P = K(T^n - T^n_{bath})$$

$$NEP = \sqrt{4\gamma k T^2 G} \cong \sqrt{4\gamma n k T P}$$

$$\frac{\Delta I}{i_n} = \frac{(1-r).P}{NEP} = (1-r)\sqrt{\frac{P}{4\gamma n k T}}$$





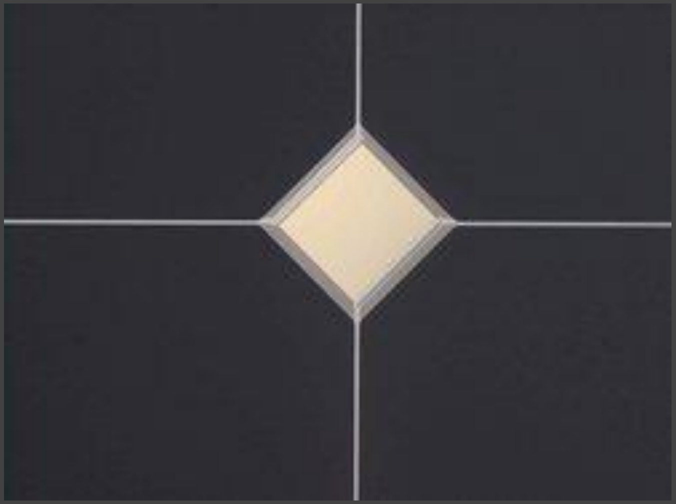
- Time constant

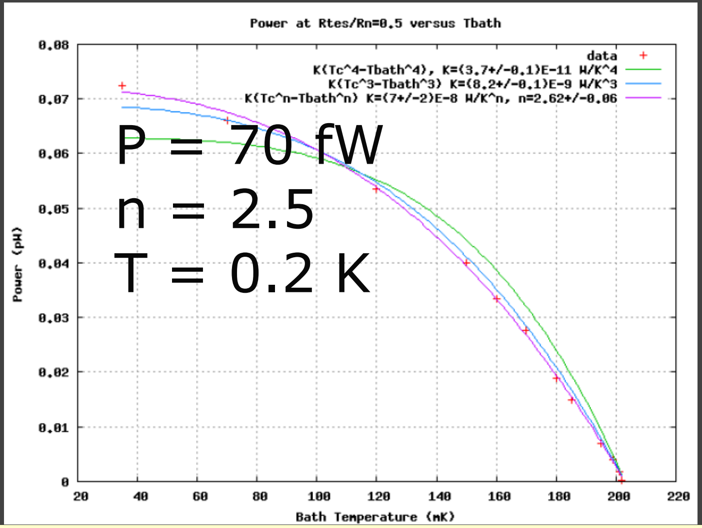
$$\tau_{eff} = \frac{C}{G}\frac{1}{1+L_0} \cong \frac{CT}{\alpha P}$$

$C/G \approx 4$ ms

NEP= 10^{-18} W/√Hz

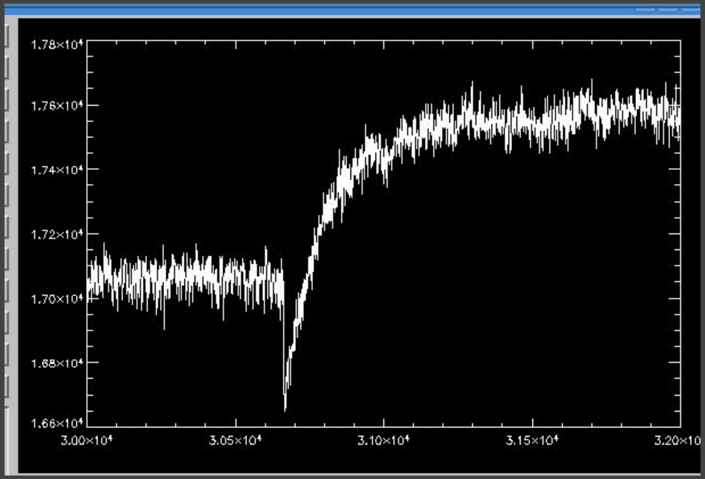
Low NEP TES-bolometer for SAFARI (SPICA)





P = 70 fW
n = 2.5
T = 0.2 K

$$NEP = \sqrt{4kT^2P} \approx \sqrt{4kTP}$$



T_C = 200 mK
100 x 100 μm TES
4 legs of 5 μm and 1.8 mm

Measured
P = 70 fW
NEP = 10^{-18} W/√Hz
τ_{eff} = 0.2 ms

Next steps:

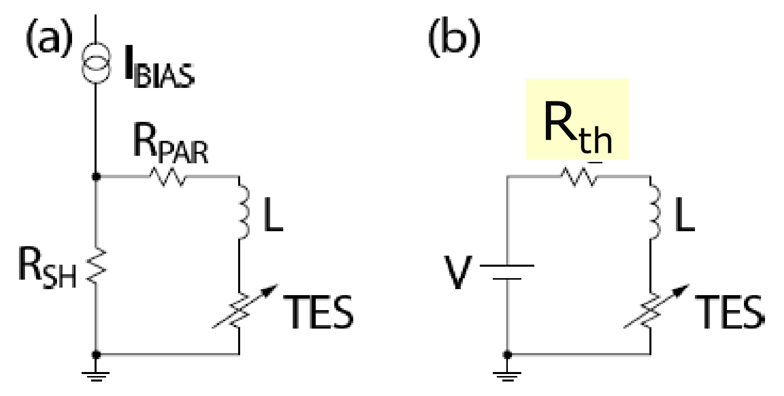
T → 100 mK
Leg width → 2 μm

Differential Equations

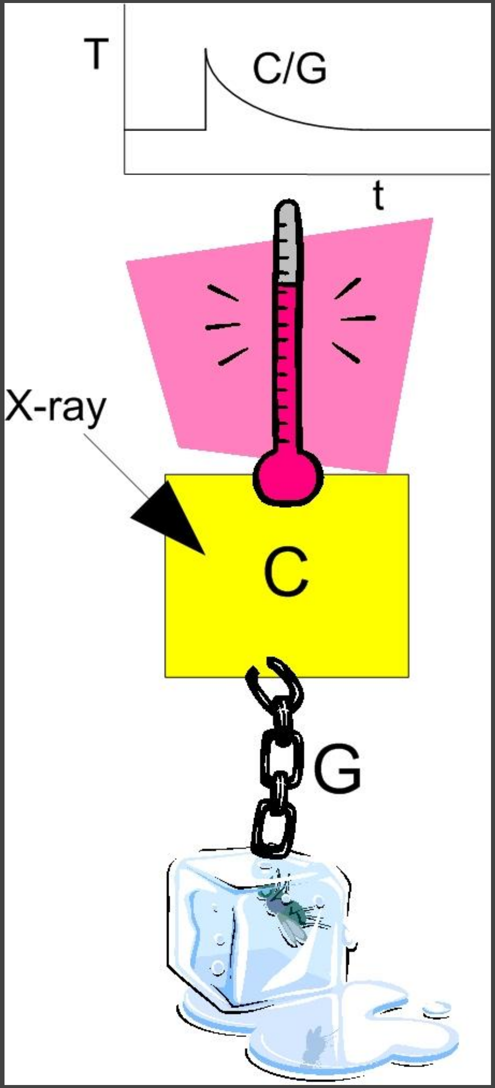
- Thermal differential equation

$$C\frac{dT}{dt}+P_{bath}+I_0.V_{Johnson}=P_{Joule}+P$$

- Electrical differential equation



$$L\frac{dI}{dT}+I.R_{th}+I.R(T,I)=V+V_{Johnson}+V_{Noise}$$



Linearizations (small signal approximation)

$$P_{bath} = K(T^n - T_{bath}^n)$$

$$G \equiv \frac{dP_{bath}}{dT} = nKT^{n-1}$$

$$P_{bath} \approx P_{bath0} + G.\Delta T$$

n = 5 electron-phonon transport
n = 4 Kapitza boundary
n = 3 Phonon transport

$$R(T,I) \approx R_0 + \alpha_I.\frac{R_0}{I_0}.\Delta I + \alpha_T.\frac{R_0}{T_0}\Delta T$$

Resistance does also depend on I through action of B-field

$$P_{Joule} = I^2.R = P_{J0} + 2.I_0.R_0.\Delta I + \alpha_I.\frac{P_{J0}}{I_0}.\Delta I + \alpha_T.\frac{P_{J0}}{T_0}.\Delta T$$

Matrix solution

$$\begin{bmatrix} \Delta I \\ \Delta T \end{bmatrix} \cdot \begin{bmatrix} i\omega L + R_{th} + R_0(1+\alpha_I) & \dfrac{R_0 I_0}{T_0}\alpha_T \\ -R_0 I_0 (2+\alpha_I) & i\omega C + G - \dfrac{P_{J0}\alpha_T}{T_0} \end{bmatrix}^{-1} = \begin{bmatrix} V_{Johnson} + V_{noise} \\ -I_0.V_{Johnson} + P \end{bmatrix}$$

Responsivity

$$S_I \equiv \Delta I / P = M_{0,1}^{-1}$$

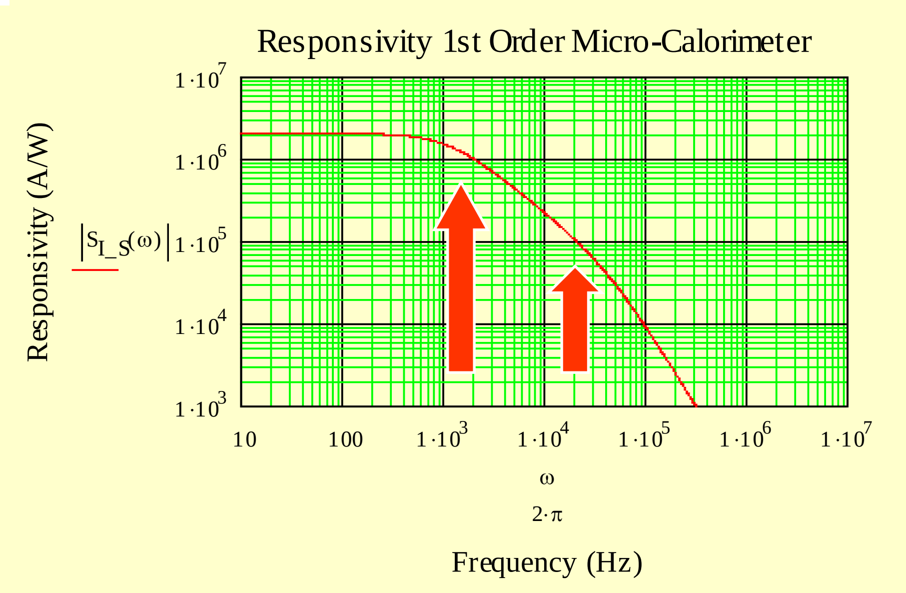
$$S_I = -\frac{1}{I_0 R_0}\left(\left(1+\frac{1+\alpha_I}{L_0}\right)(1+i\omega\tau_{fall}) + \frac{R_{th}+i\omega L}{R_0}\left(1-\frac{1}{L_0}\right)(-1+i\omega\tau_{eff})\right)^{-1}$$

With $L_0 = \dfrac{\alpha.P}{G.T}$ the electro-thermal loop gain and $\tau_{eff} = \tau_0 / L_0 - 1$

This equation shows one pole (fall time) at : $\tau_{fall} = \dfrac{C}{G}\dfrac{1}{1+L_0/(1+\alpha_I)}$

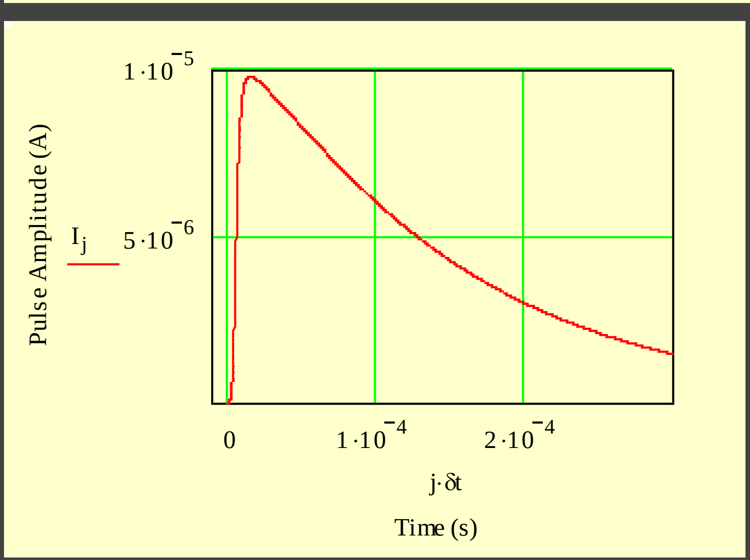
And a 2nd pole (rise time) at : $\tau_{el} = L/(R_{th} + R_0(1+\alpha_I))$

Typical Micro-calorimeter Responsivity



$C = 0.5$ pJ/K
$G = 0.35$ nW/K ($P = 9$ pW)
$\alpha_T = 100$
$\alpha^I = 1$
$T = 0.1$ K
$L_0 \rightarrow 25$

$R_0 = 40$ mOhm
$R_{th} = 10.6$ mOhm
$L = 600$ nH



1st pole 1.5 kHz/110 μs
(signal fall time)

2nd pole 24 kHz/6.7 μs
(signal rise time)

Matrix solution

$$\begin{bmatrix} \Delta I \\ \Delta T \end{bmatrix} . \begin{bmatrix} i\omega L + R_{th} + R_0(1+\alpha_I) & \dfrac{R_0 I_0}{T_0}\alpha_T \\ -R_0 I_0(2+\alpha_I) & i\omega C + G - \dfrac{P_{J0}\alpha_T}{T_0} \end{bmatrix}^{-1} = \begin{bmatrix} V_{Johnson} + V_{noise} \\ -I_0.V_{Johnson} + P \end{bmatrix}$$

Thermal fluctuation noise

$$I_{Phonon} = P_{phonon} M_{INV}(0,1)$$

Johnson Noise

$$I_{Johnson} = V_{Johnson}[M_{INV}(0,0) - I_0 M_{INV}(0,1)]$$

Shunt noise

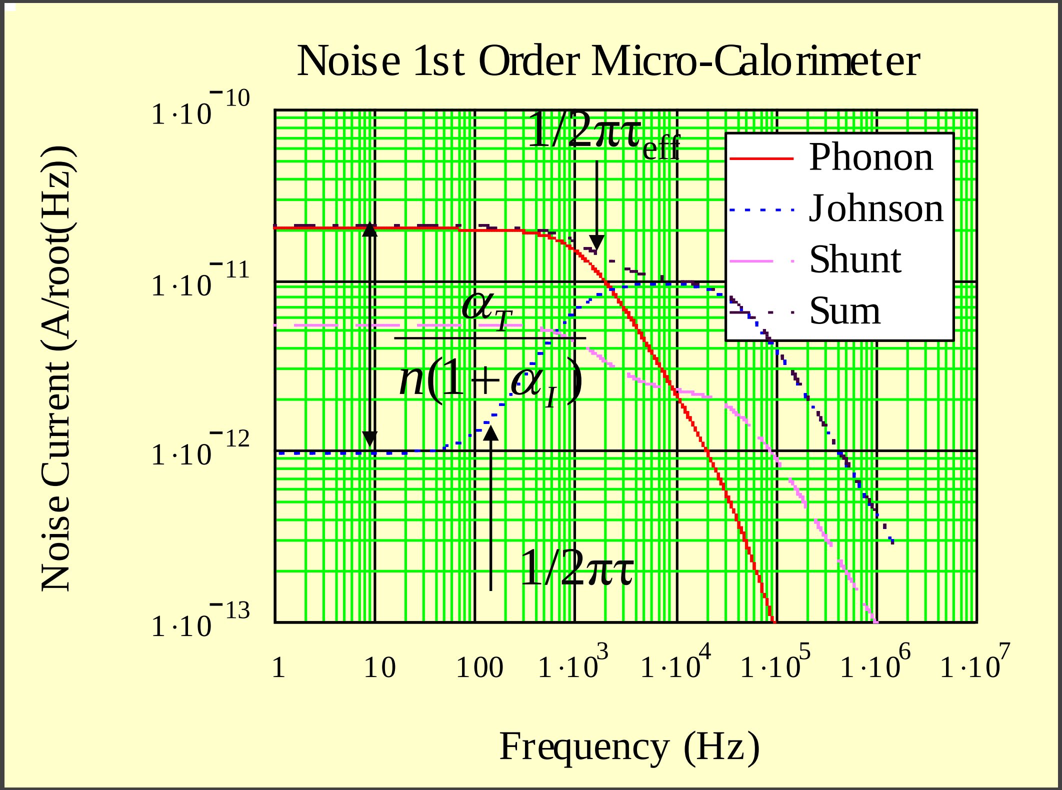
$$I_{shunt} = V_{noise} M_{INV}(0,0)$$

Micro-Calorimeter Noise sources

1) Phonon Noise $P_{Phonon} = \sqrt{4kT^2G\Gamma}$ in W/√Hz with $\Gamma \approx 0.5$

2) Johnson Noise $V_{Johnson} = \sqrt{4kTR\xi}$ in V/√Hz with $\xi = 1 + 2\alpha_I$

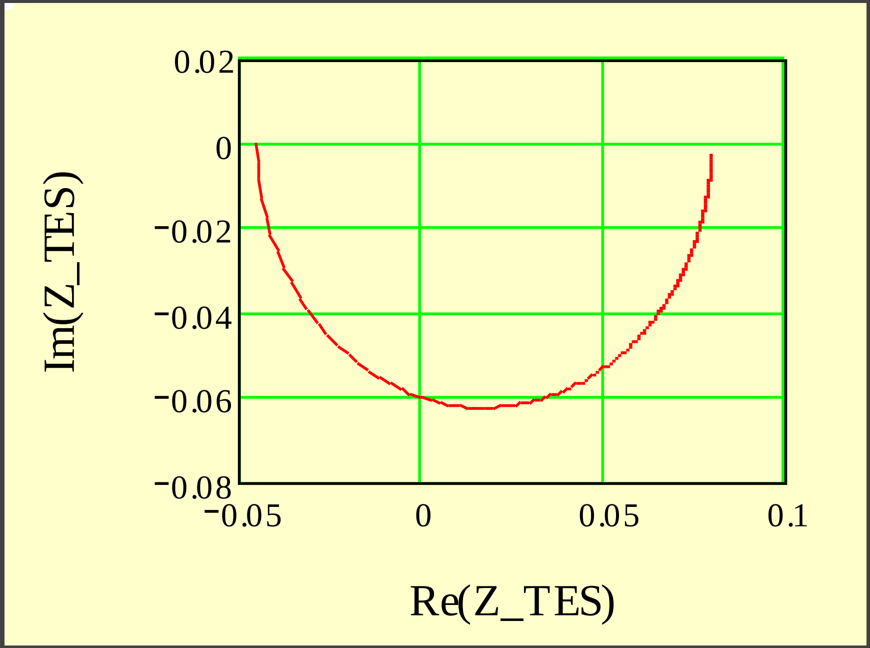
3) Shunt noise $V_{shunt} = \sqrt{4kT_{sh}R_{sh}}$ in V/√Hz



R_{sh} = 10.6 mΩ
T_{sh} = 60 mK

Complex Impedance

$$Z_{TES} = M_{INV}^{-1}(0,0) - (R_{th} + i\omega L)$$



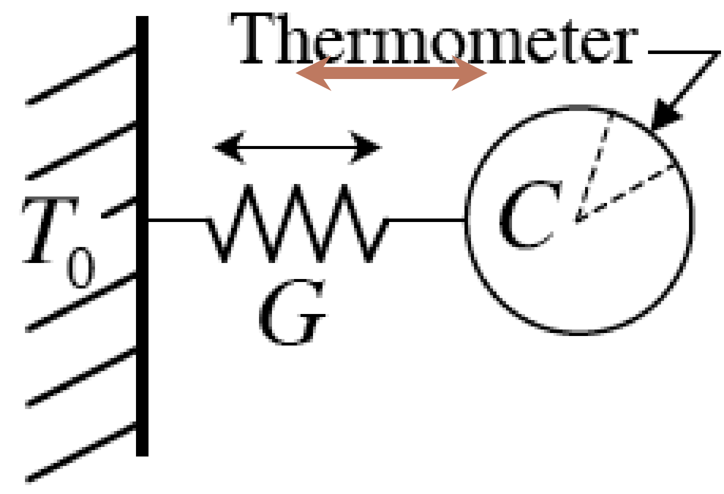
$$Z(0) = -R_0 \frac{1 + \alpha_I + L_0}{L_0 - 1}$$

$$Z(\infty) = R_0(1 + \alpha_I)$$

$$\tau_{eff} = \frac{\tau_0}{L_0 - 1}$$

The effective time constant equals 1/ω for the minimum imaginary number

Energy Resolution



Random transport of energy between heat sink and detector over thermal link G produces fluctuations in the energy content of C. The magnitude of these can easily be calculated from the fundamental assumption and definitions of statistical mechanics:

$$\boxed{\sigma_E^2 = \mathrm{k}\,T^2 C}$$

“Thermodynamic Fluctuation Noise” (TFN)

Can think of as Poisson fluctuations in number of energy carriers in C with mean c

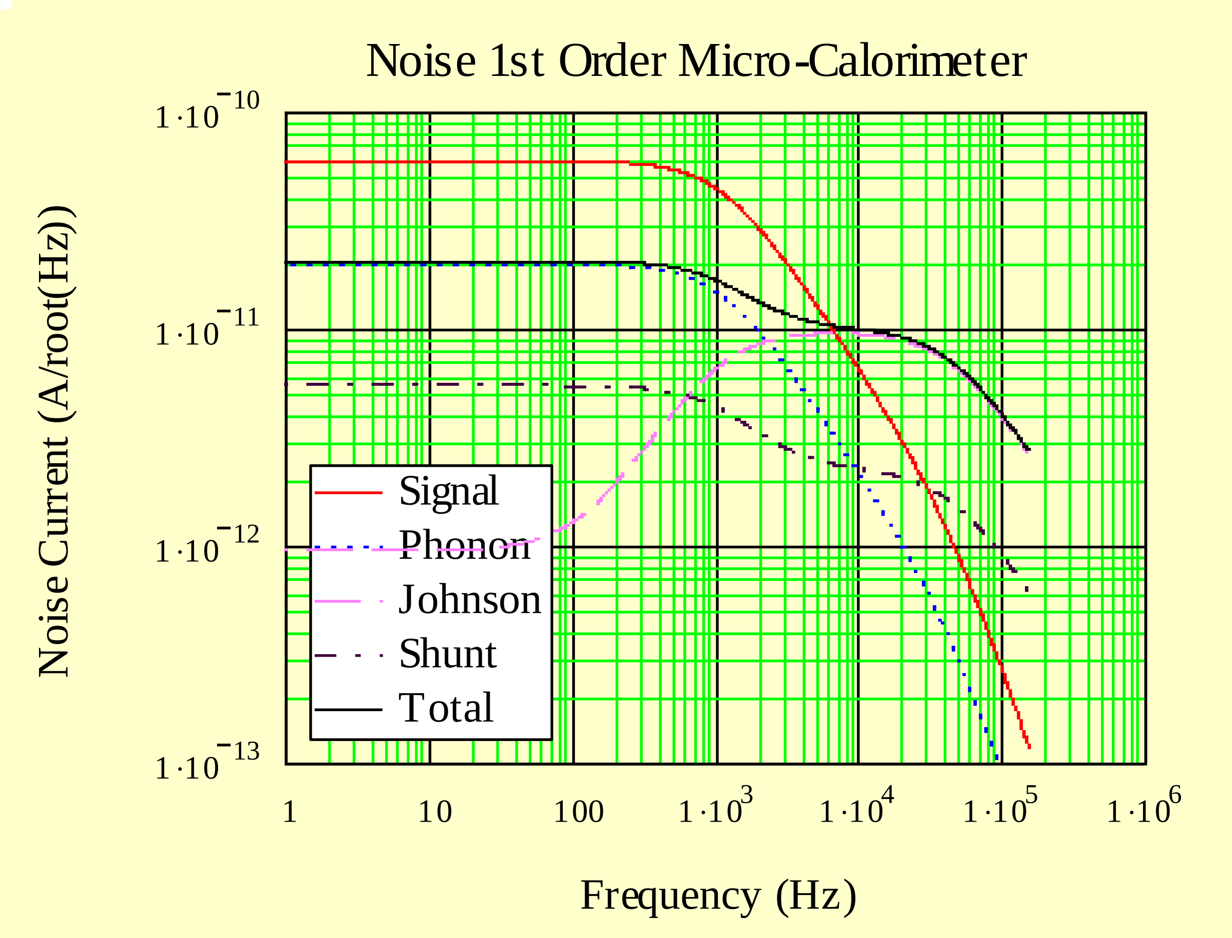
$$N \approx \frac{CT}{\mathrm{k}T}, \quad \Delta E_{rms} = \sqrt{N} \cdot (\mathrm{k}T) = \sqrt{\mathrm{k}T^2 C}$$

.)

Not a limit on resolution, but sets the scale . . .

Energy Resolution

- Noise in different frequency bins uncorrelated
- Each frequency bin gives independent estimate of signal amplitude
- ∴



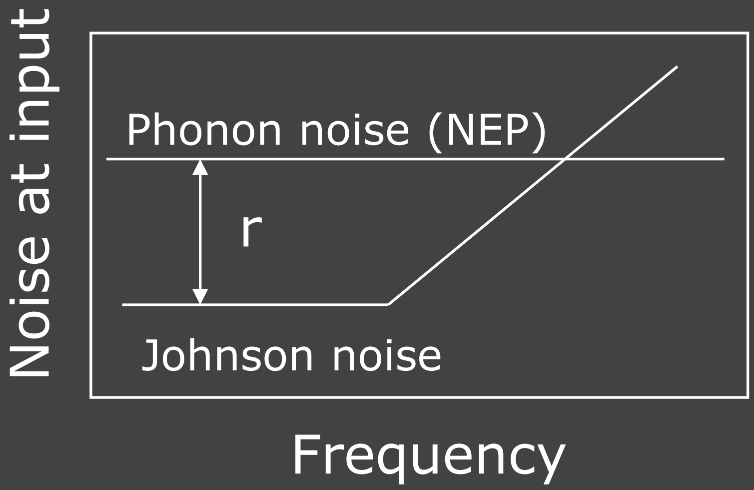
Energy Resolution in time domain

$$\Delta E = 2\sqrt{2\ln 2}\,NEP(0)\sqrt{\tau^*}$$

1/2πτ* frequency where Johnson noise and TFN cross each other

$$NEP(0) = \sqrt{4kT^2 G\Gamma}$$

with Γ = 0.5



$$\tau^* = \frac{C}{G}\frac{1}{r}$$

$$1/r = \sqrt{\frac{4kT/R}{4kT^2 G\Gamma}}\,\frac{1}{L_{eff}}\,V\,\frac{1+L_{eff}}{L_{eff}} \approx \frac{1+\alpha_I}{\alpha_T}\sqrt{\frac{n(1+2\alpha_I)}{[1+\left(\frac{T_0}{T}\right)^n].\Gamma}}$$

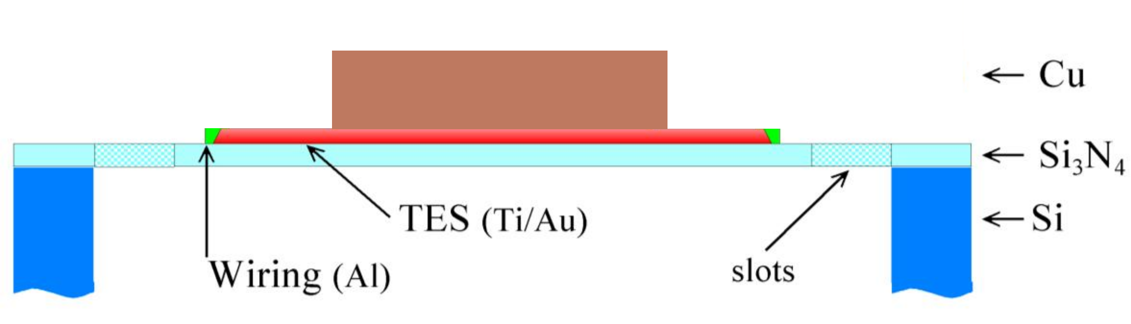
For C = 0.5 pJ/K, n = 3, α_T = 100, α_I = 1, and T = 0.1 K we get:
ΔE = 1.64 eV

Detector Characterization

Full Characterization includes:

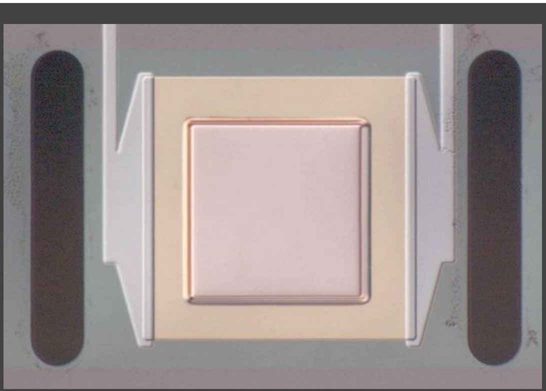
- RT measurements
- IV, f(T_{bath}, magnetic field)
- Complex impedance
- Noise
- Baseline + X-ray energy resolution

Example: central Cu absorber

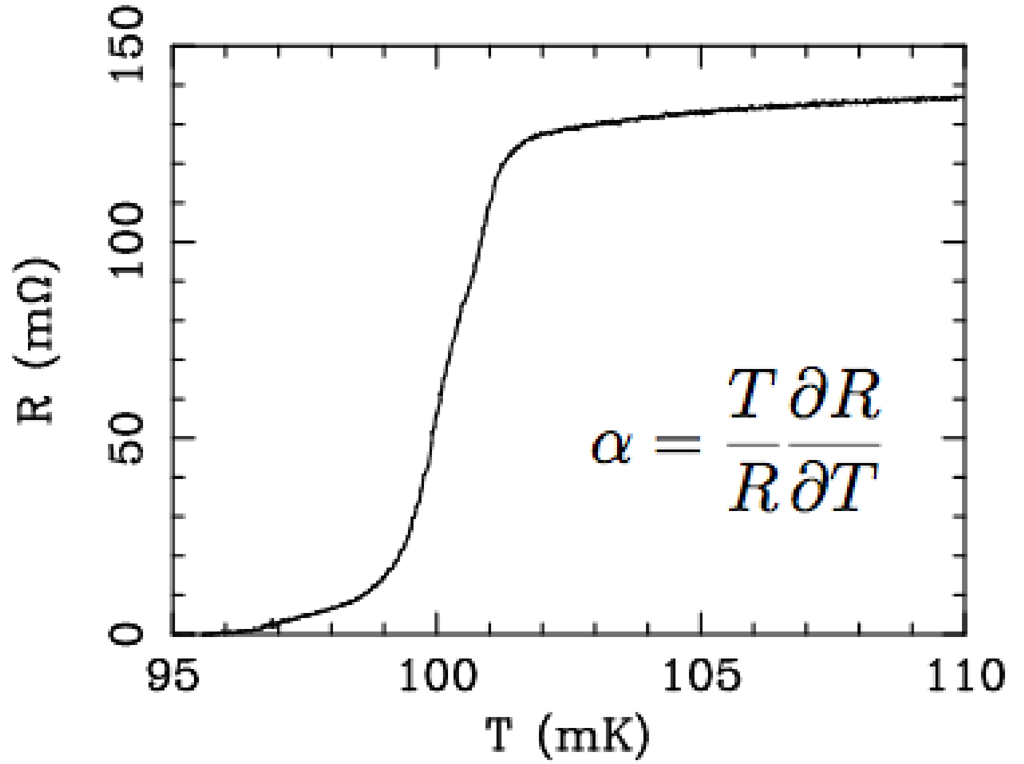


TES: TiAuTi
thickness: 20/50/5 nm
size: 146×150 μm^2

absorber: Cu
thickness: 1 μm
size: 100×100 μm^2



RT measurements

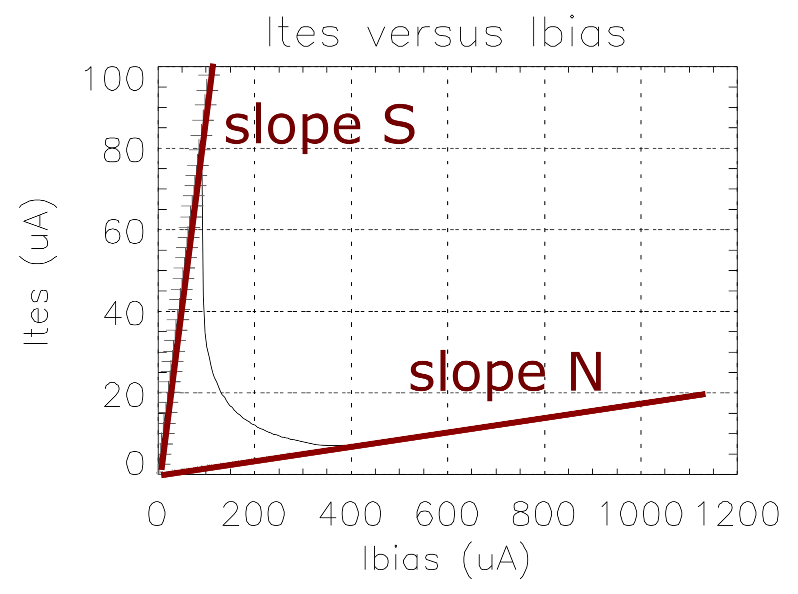


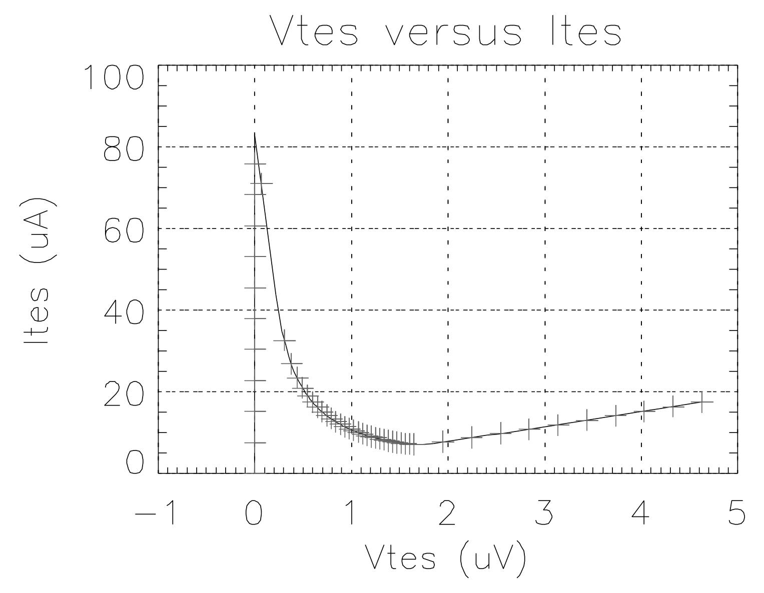
$$\alpha = \frac{T}{R}\frac{\partial R}{\partial T}$$

***RT* profile with small current**

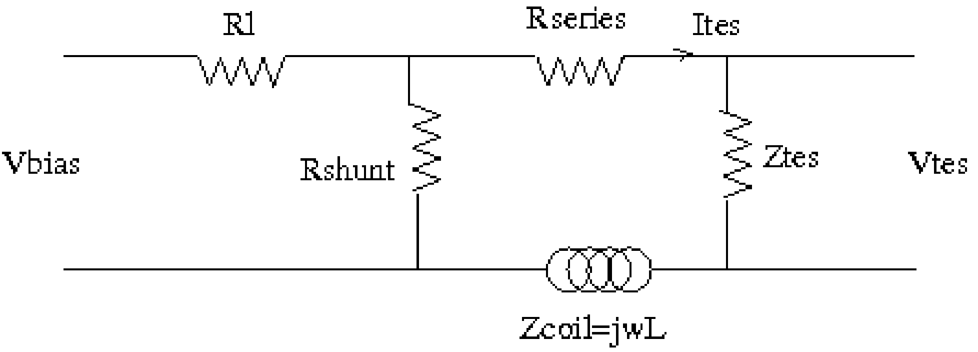
- Ti/Au bilayer with a Cu absorber
- T_C = 100 mK
- R_n = 143 mΩ

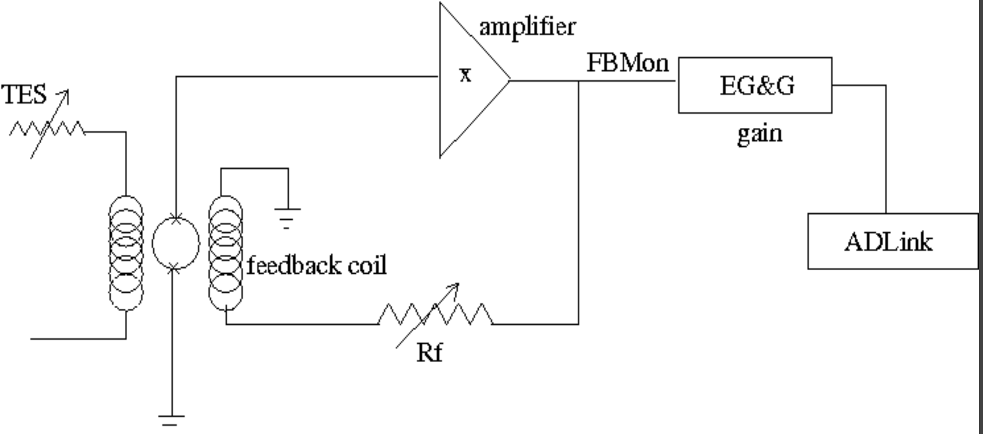
IV measurements





Bias circuit





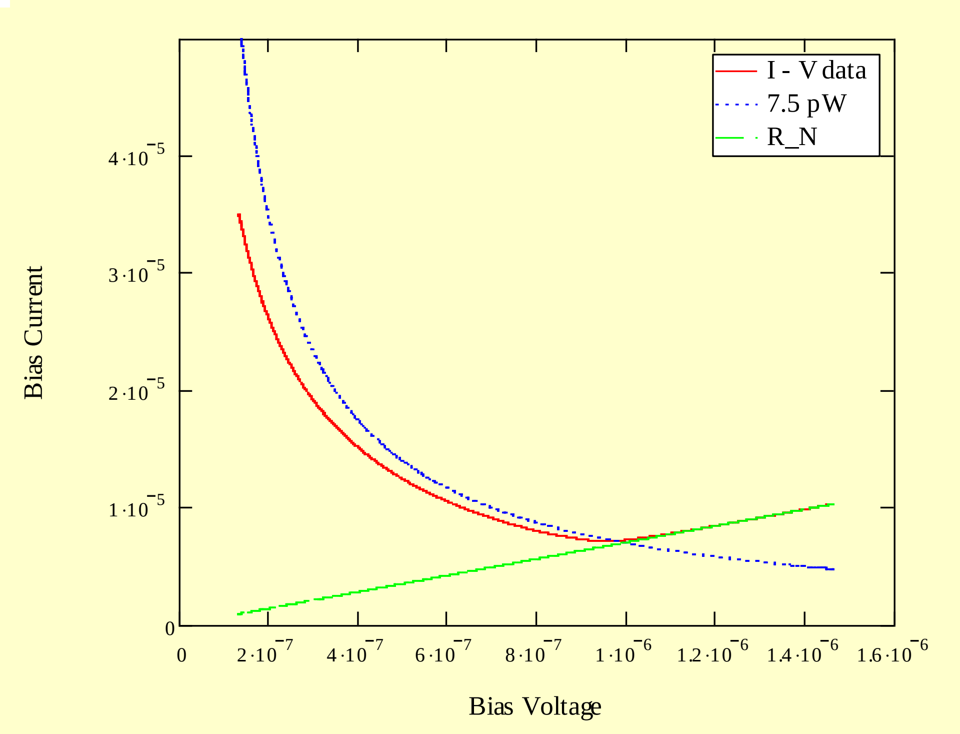
Read-out

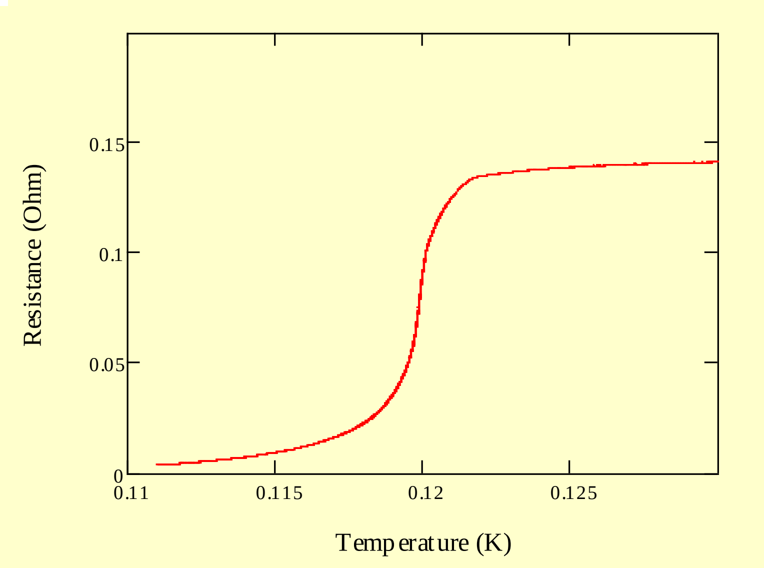
Ptes (V)
With n, T_C,
→ R(T) and

$$\alpha_{eff} = \frac{\alpha_T}{1+\alpha_I/2}$$

I – V Analysis

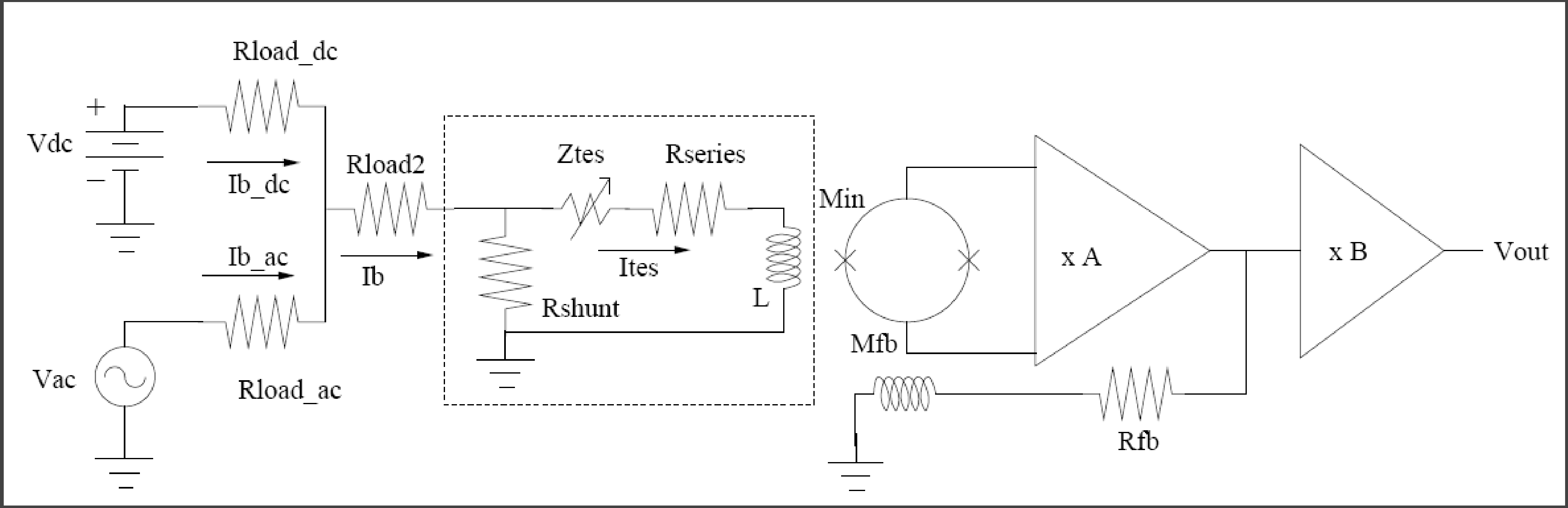
With knowledge of n (from P (T_bath) measurements, and T_C (From R(T)) we can derive the R(T) from I – V, which is not equal to the R(T) obtained by scanning in T with a constant measurement current





$$\alpha_{eff} = \frac{\alpha_T}{1+\alpha_I/2}$$

Complex impedance



Bias scheme with:

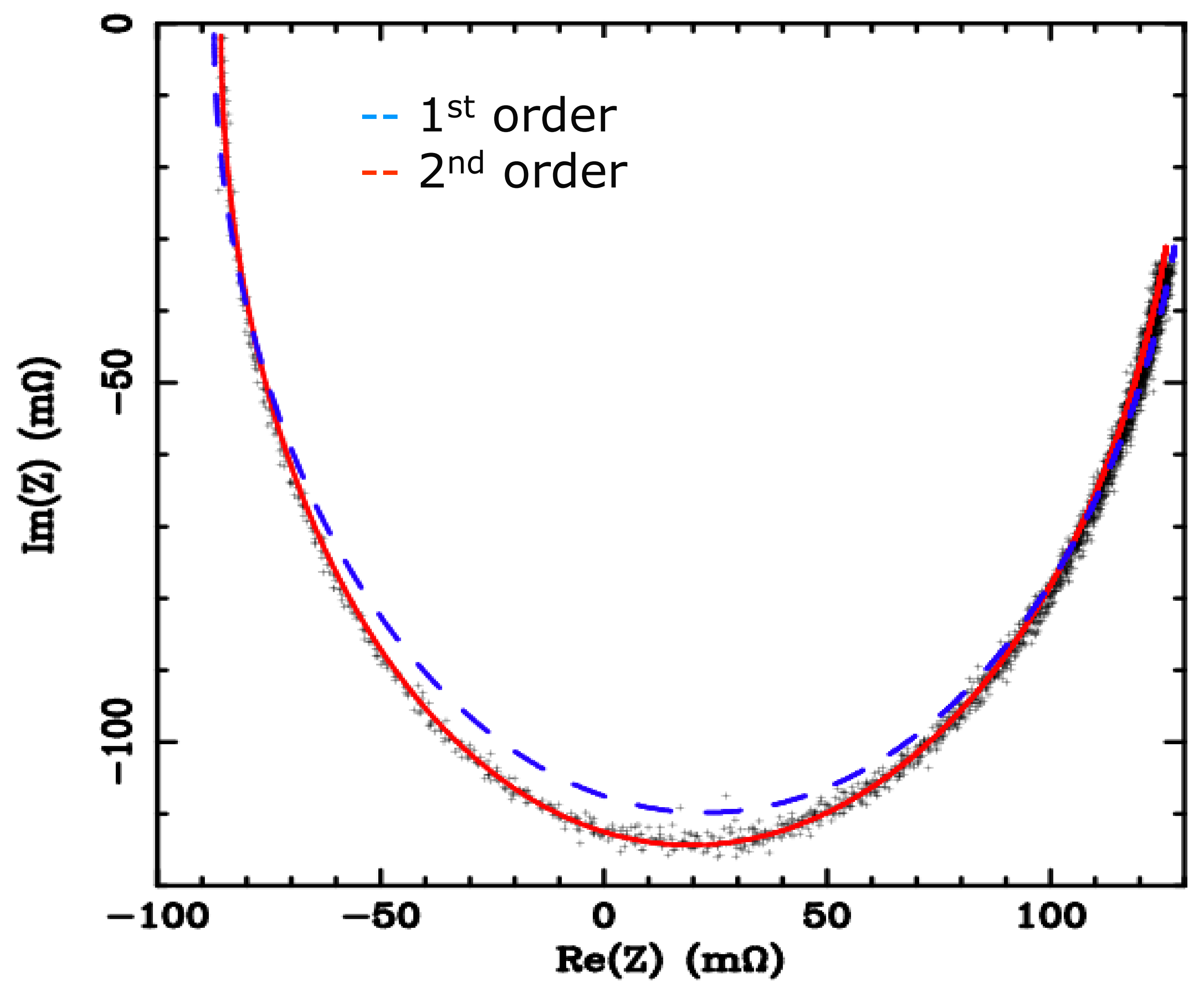
$$\overline{Z}_{TES}(j\omega) = \frac{\overline{V}_{AC}(j\omega)}{(R_{loadAC} + R_{load2})} \cdot \frac{R_{shunt}}{\overline{I}tes(j\omega)} \overline{T}(j\omega) - \overline{Z}_{Th}(j\omega)$$

$$\overline{Z}_{Th}(j\omega) = R_{series} + R_{shunt} + jwL$$

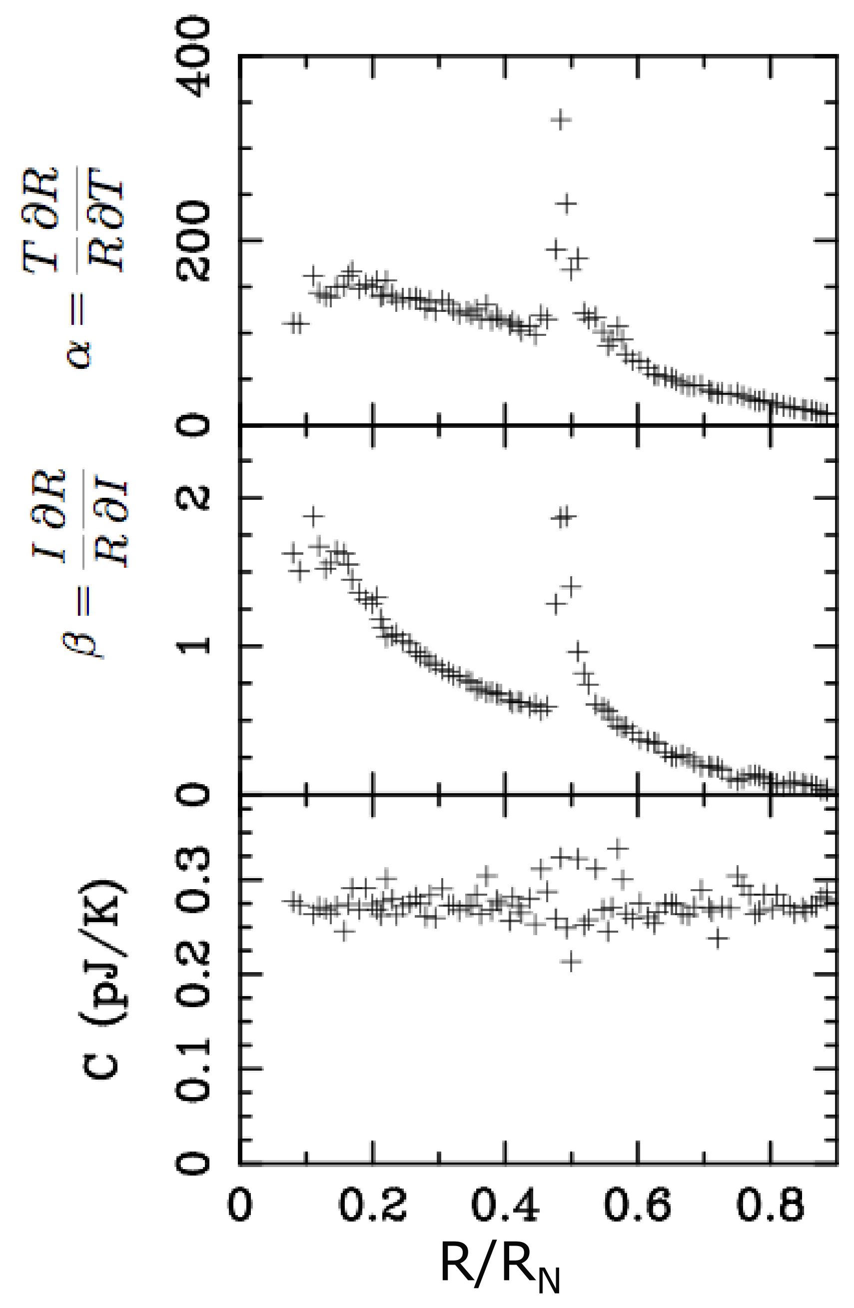
T(jw) : transfer function of the signal lines → determined experimentally

Znormal/Zsuper gives L, then Zsuper leads to determination of T(jw)

Complex impedance



Complex impedance



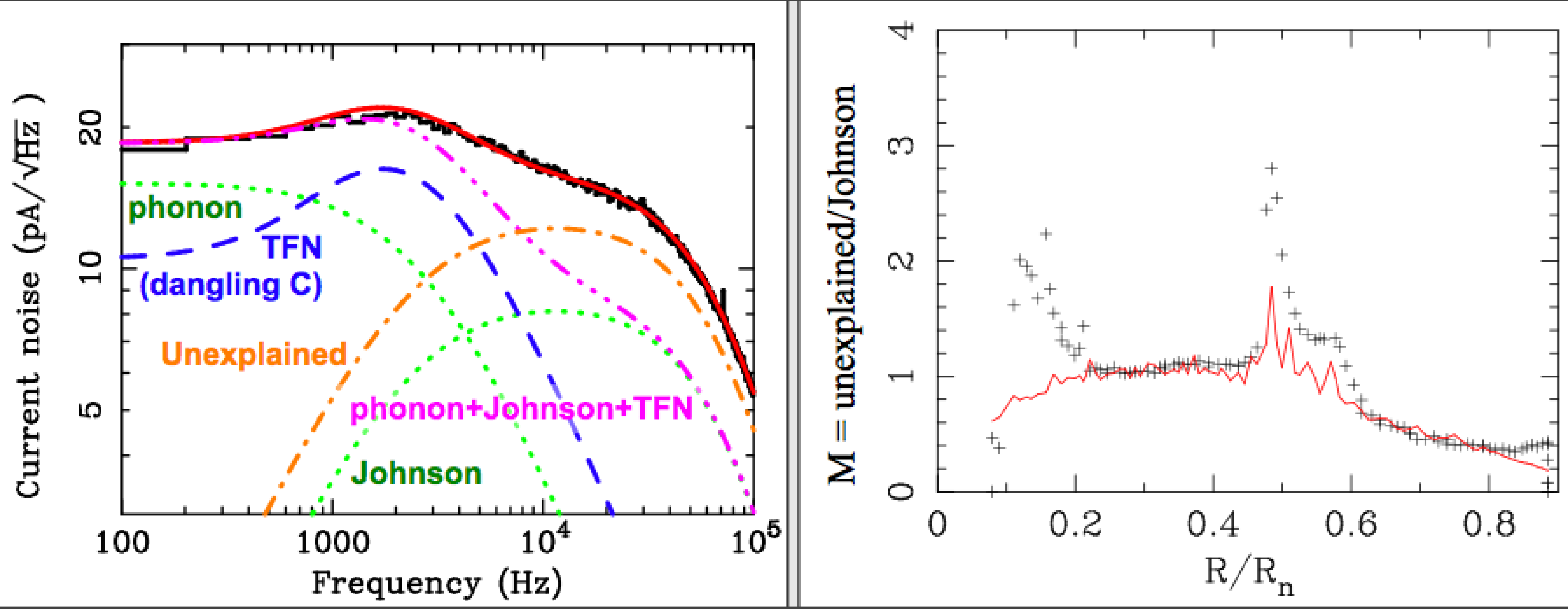
2nd order due to “dangling” heat capacity with:

C_D = 0.04 pJ/K

G_D = 0.4 nW/k (τ_D = 0.1 ms)

Noise (Measurement and Model)

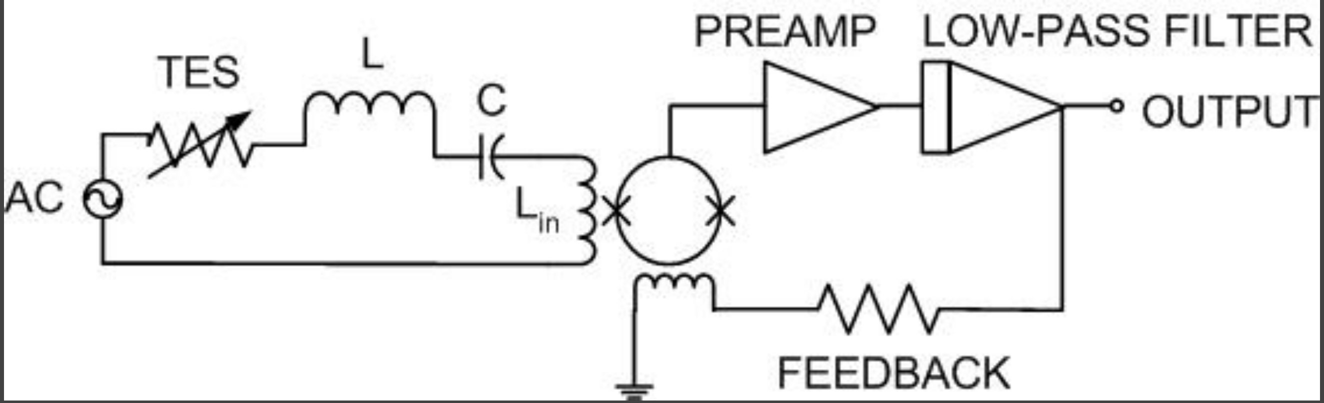
variables from complex impedance
used to fit noise spectra:

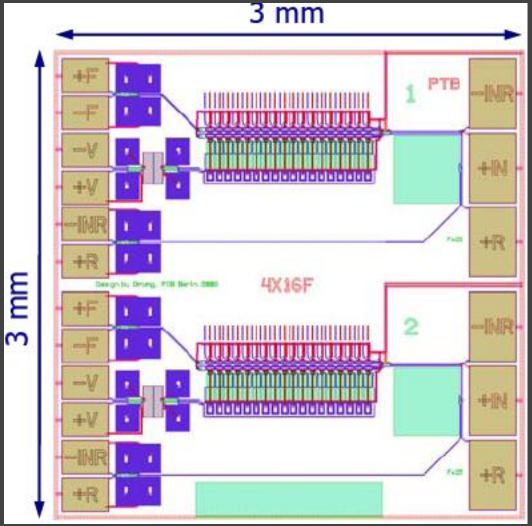


Read-out Electronics

1) SQUID-amplifier
2) Multiplexing
    1) Introduction
    2) FDM
    3) (Baseband) Feedback
        1) Principle
        2) Characteristics
        3) Implementation
3) LC-filters

TES READ-OUT BY SQUID AMPLIFIER





PTB 16-SQUID-arrays

Typical SQUID parameters:

$L_{in} = 3$ nH

$Ø_n = 0.22\ \mu Ø_0/\sqrt{\text{Hz}}$

$i_N = 5\ \text{pA}/\sqrt{\text{Hz}}$

Dyn.Range +/- 0.45 $10^6\ \sqrt{\text{Hz}}$

Signal Characteristics:

$$i_{Johnson} = \sqrt{4kT/R} \quad = 12\ \text{pA}/\sqrt{\text{Hz}}$$

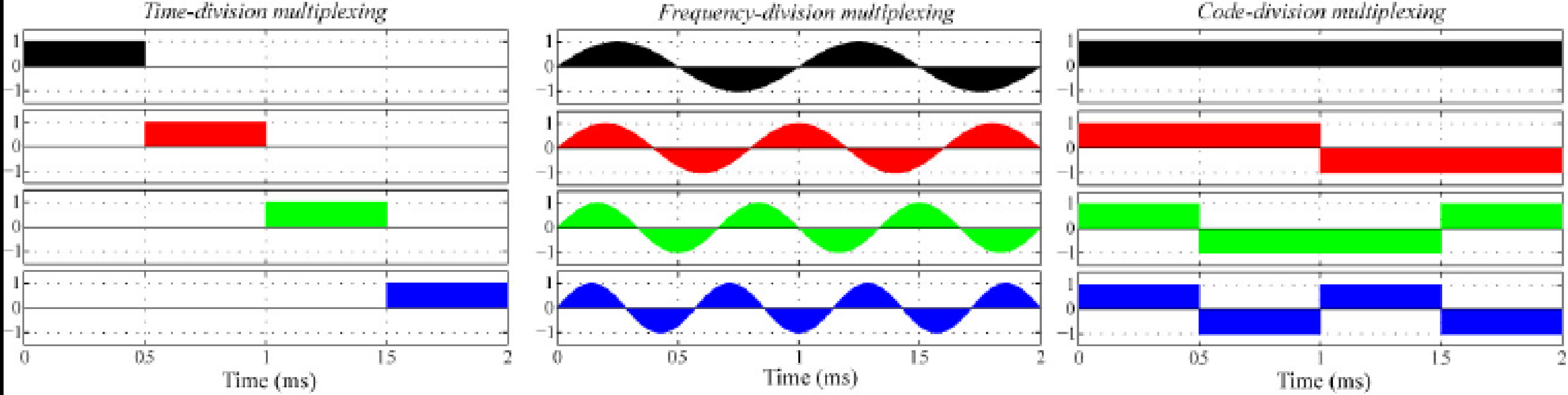
$$Dyn.Range = \frac{E_{max}}{\Delta E_{rms}\sqrt{\tau}} \quad = +/-10^6\sqrt{\text{Hz}}$$

Noise levels ok

SQUID dynamic range ≈ 6x too small → feedback required for dynamic range and linearization

Multiplexing

Multiplexing basis sets



Time-division (e.g. TDMA cell phones)

- Classic SQUID multiplexer circuits that switch by turning on SQUIDs (or shunting with flux-actuated switches).

Frequency-division (e.g. FDMA cell phones)

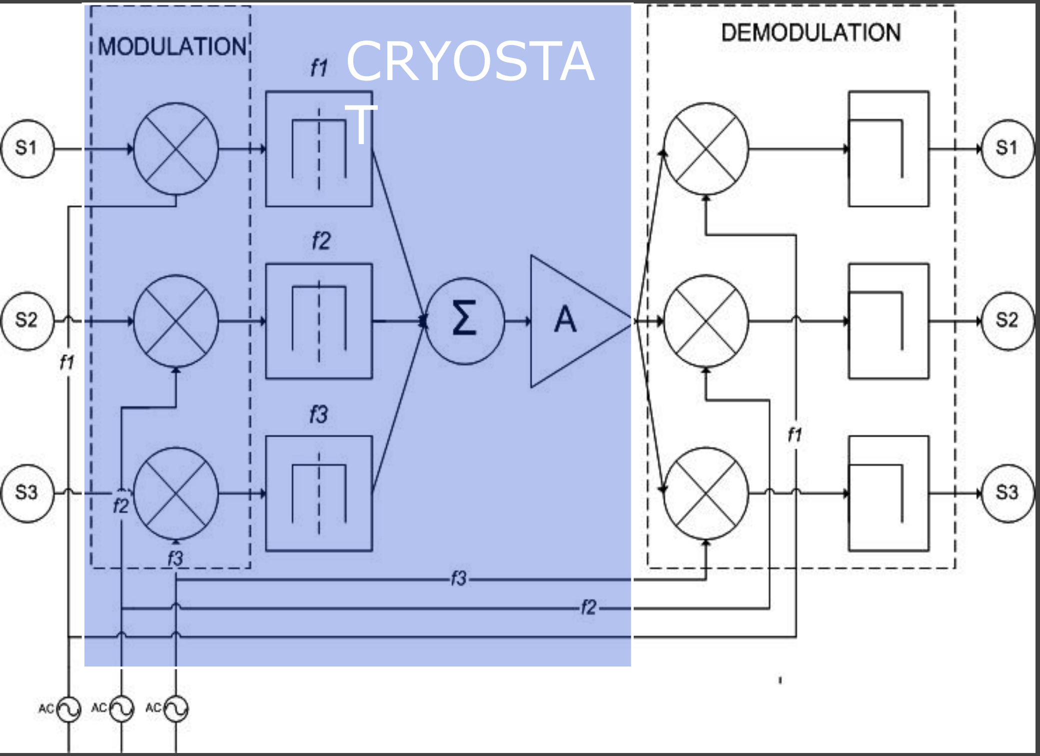
- Under development in SRON and Japan

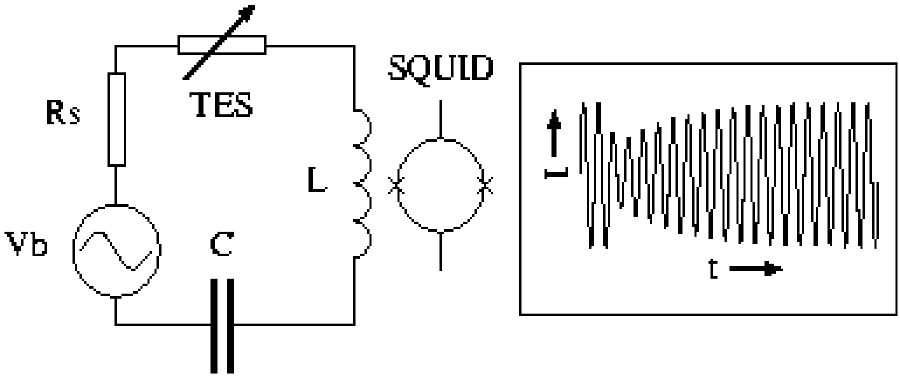
Code-division (e.g. CDMA cell phones)

1. Uses same room-temperature electronics as TDM (“TDM Turbo”)
2. Only one SQUID per column
3. Ultra-low-power switches modulate polarity of coupling
4. Detectors dc biased
5. No multiplex disadvantage

Courtesy to Kent Irwin

FREQUENCY-DOMAIN-MULTIPLEXING





1 column or row of pixel-array shown as example

FDM operation:

- TESs act as AM-modulators

- TESs AC-biased at frequencies *f1, f2, f3*, ….

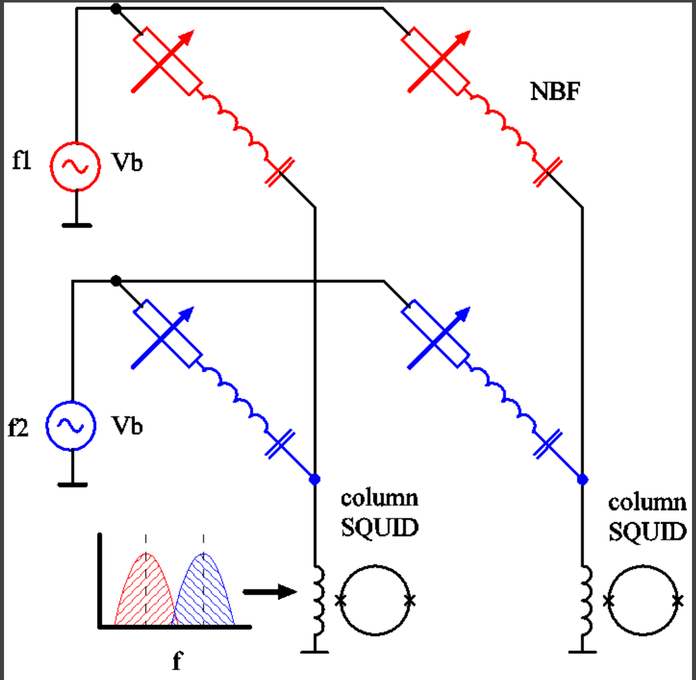
-Each TES equipped with LC band pass filter around carrier frequency to block wide-band noise

- Summed signal read-out by one SQUID-amplifier per column

- Demodulation by amplification and filtering

FREQUENCY DOMAIN MULTIPLEXING

Design Issues



$$R_{ESR} = \frac{\omega L}{Q} < R_{sh}$$

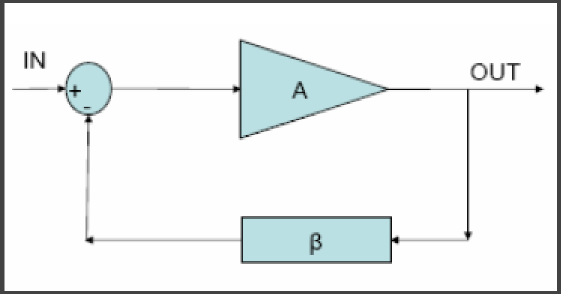
$$\omega = \frac{R}{k_c^2 L_{in}}$$

1) Summing topology
2) Chosen for current summing
3) Feedback required to minimize common impedance, linearize SQUID response, and increase dynamic range
4) LC-filter inductance set by TES stability requirements. Critical damping sets L ≈ 1 μH, for R = 40 mΩ and $\alpha_I = 1$

$$L/R = \frac{1}{2}(3 + \alpha_I - 2\sqrt{2 + \alpha_I})\tau_{eff}$$

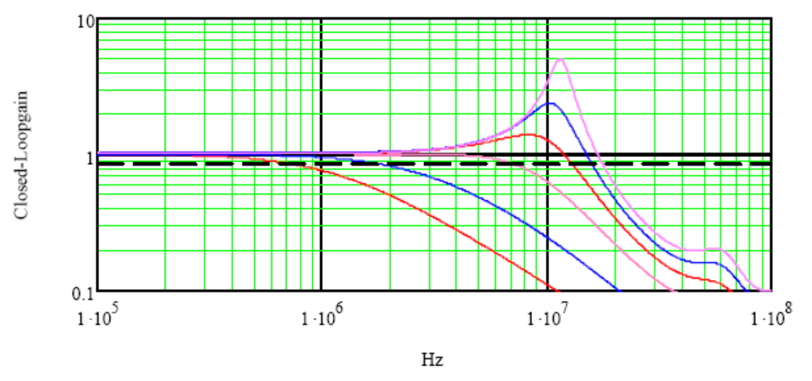
5) 1 – 10 MHz frequency range
   > 1 MHz LC-filter capacitance large at low f
   < 10 MHz due to SQUID back action noise (L_{in} < 0.6 nH for k_c = 1), and LC-filter losses (Q > 10.000)
6) Frequency spacing (> 50 kHz to keep crosstalk low)

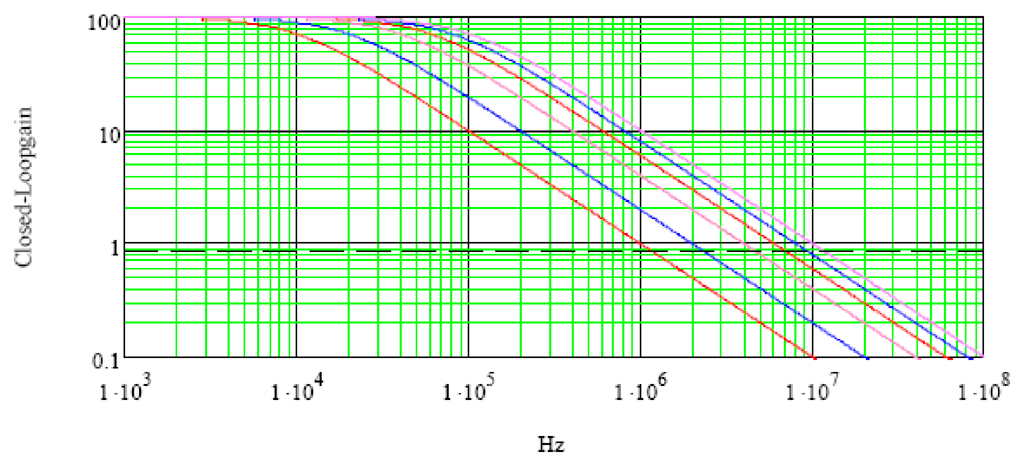
Standard FLL limitations



$$f_{1,\max} = \frac{1}{4\pi t_d} = \frac{0.08}{t_d}$$

Delay in FLL seriously limits the available bandwidth





Closed loop response for β=1 and for β = 0.01 and a 20 ns delay Resulting in a maximum stable f_1 = 8 MHz. So for 6x loopgain only a bandwidth of 1.3 MHz is available

Baseband feedback

Use the fact that:

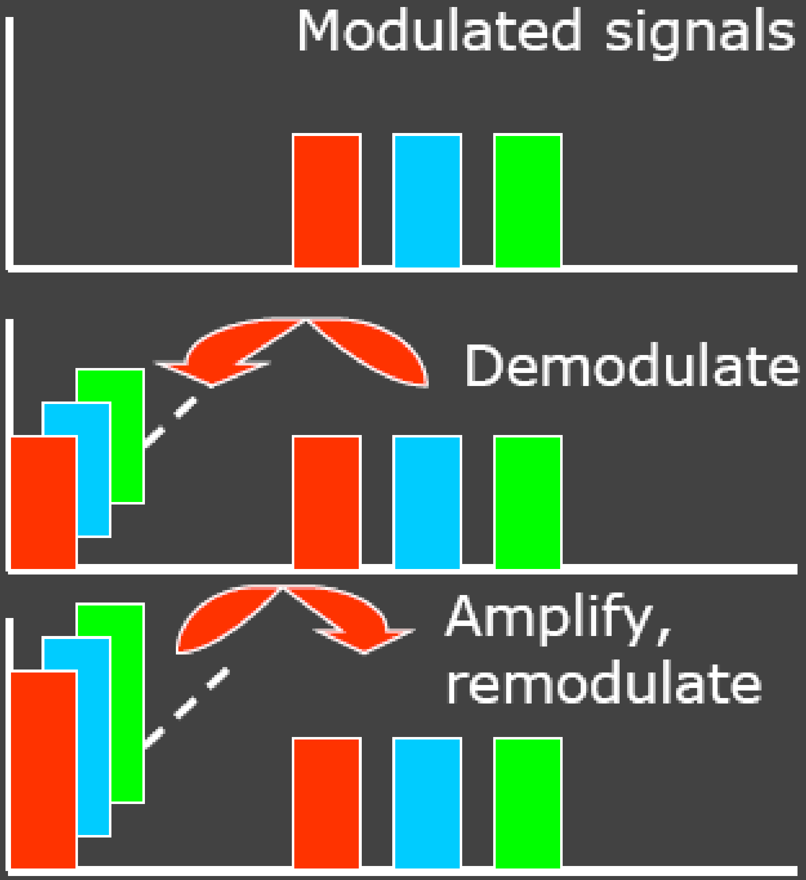
- ➢ Only the envelope contains information
- ➢ The carrier is deterministic

⇒Feedback on envelope only

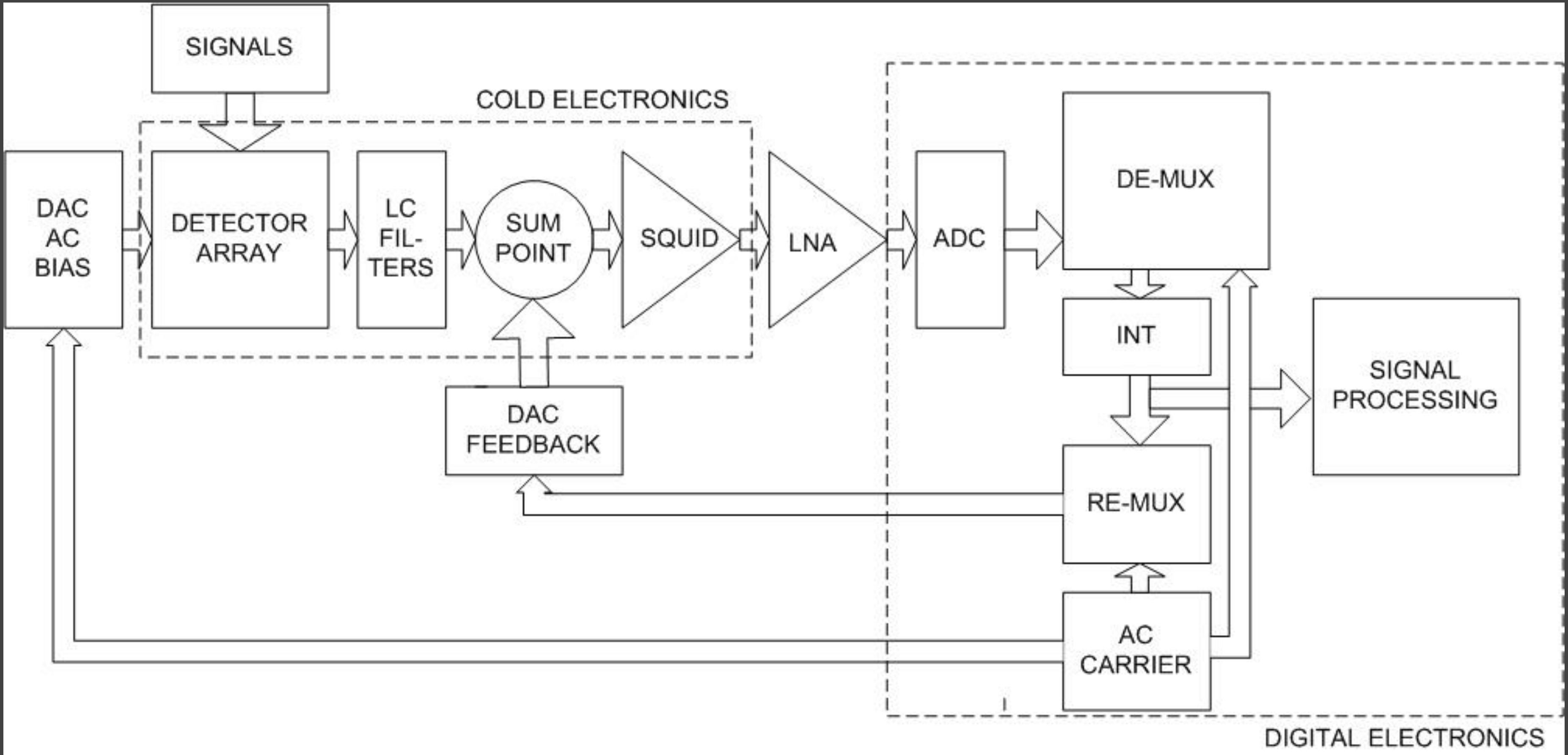
⇒One channel per pixel

⇒Maximum GBW set by channel separation (GBW ≈ Δf/6)

⇒Very similar to the frame rate limitation in TDM on GBW



Baseband feedback implementation

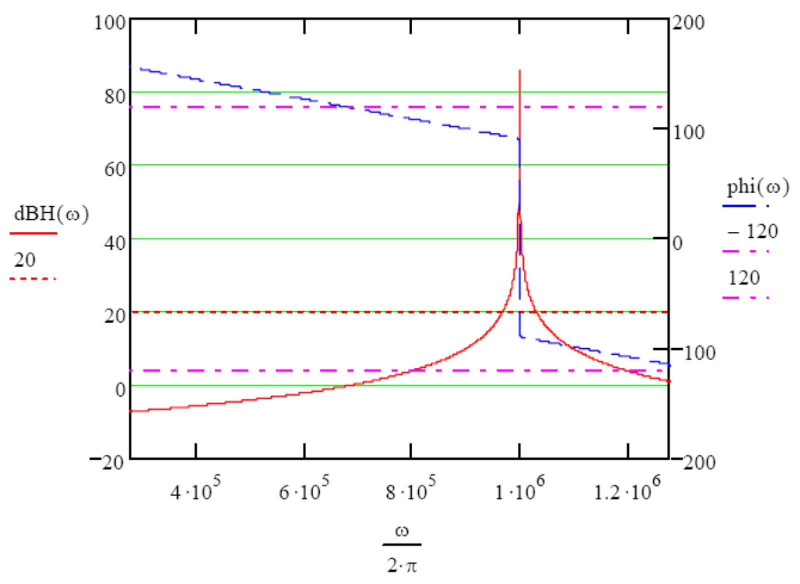


SRON

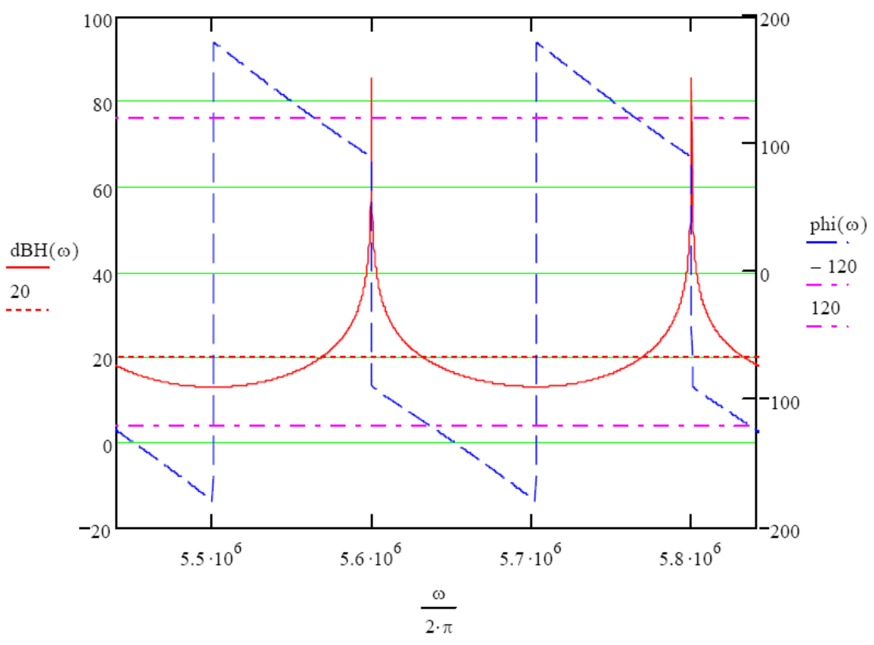
Baseband Feedback Filter characteristics

$$H(\omega) = \frac{e^{-j(\omega T_d - \varphi)}}{1 + j(\omega - \omega_c)\tau}$$

The transfer function around each carrier frequency consists of an integrator, a delay term and a phase compensation of the delay



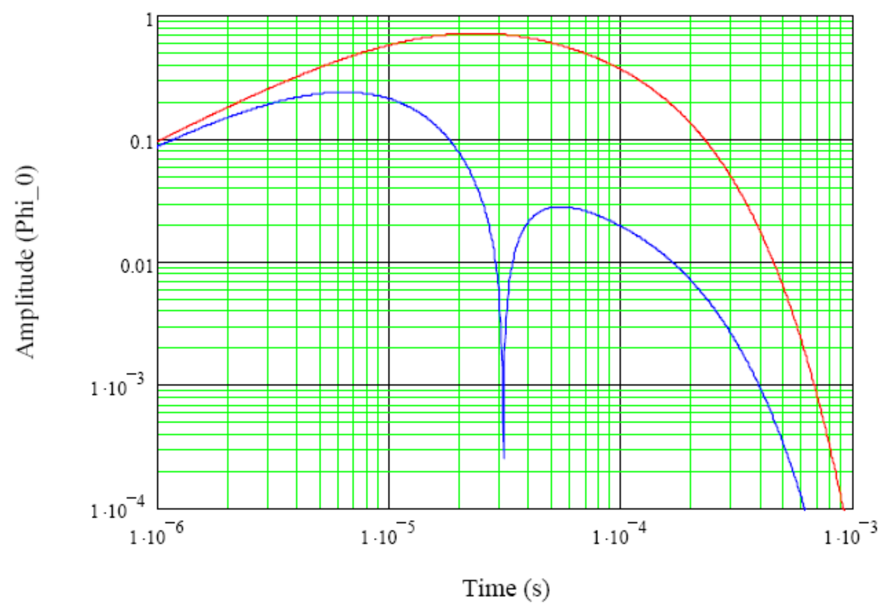
Amplitude and phase for a single Carrier (250 ns delay)



Amplitude and phase of two central carriers out of 32

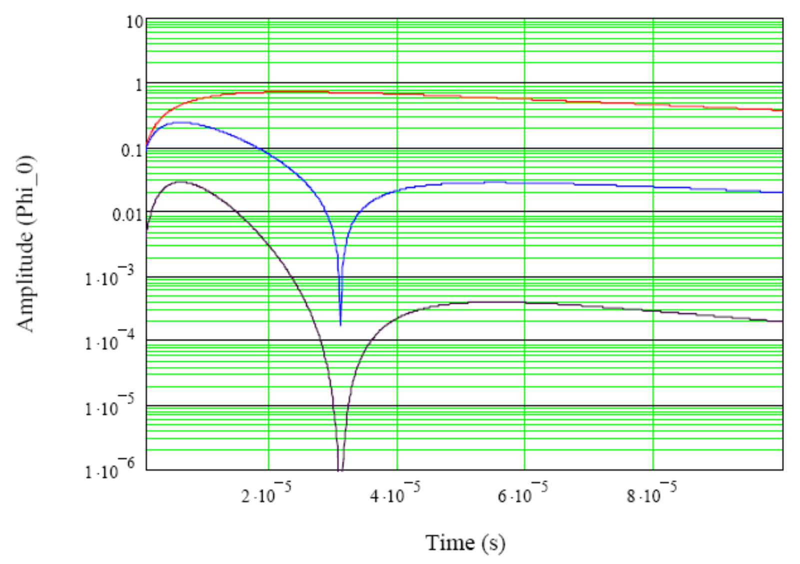
For a 60⁰ phase margin the Gain-bandwidth around each carrier is limited to about Δf/6, i.e. 33 kHz for 200 kHz carrier separation

Simulations on error signal and 2^{nd} harmonic



- Signal amplitude of 1 $Ø_0$ (0.2 $\mu Ø_0/\sqrt{Hz}$ noise and +/- 5 10^6 $\sqrt{Hz}$ dyn. Range)
- Signal with 10 µs risetime and 100 µs falltime

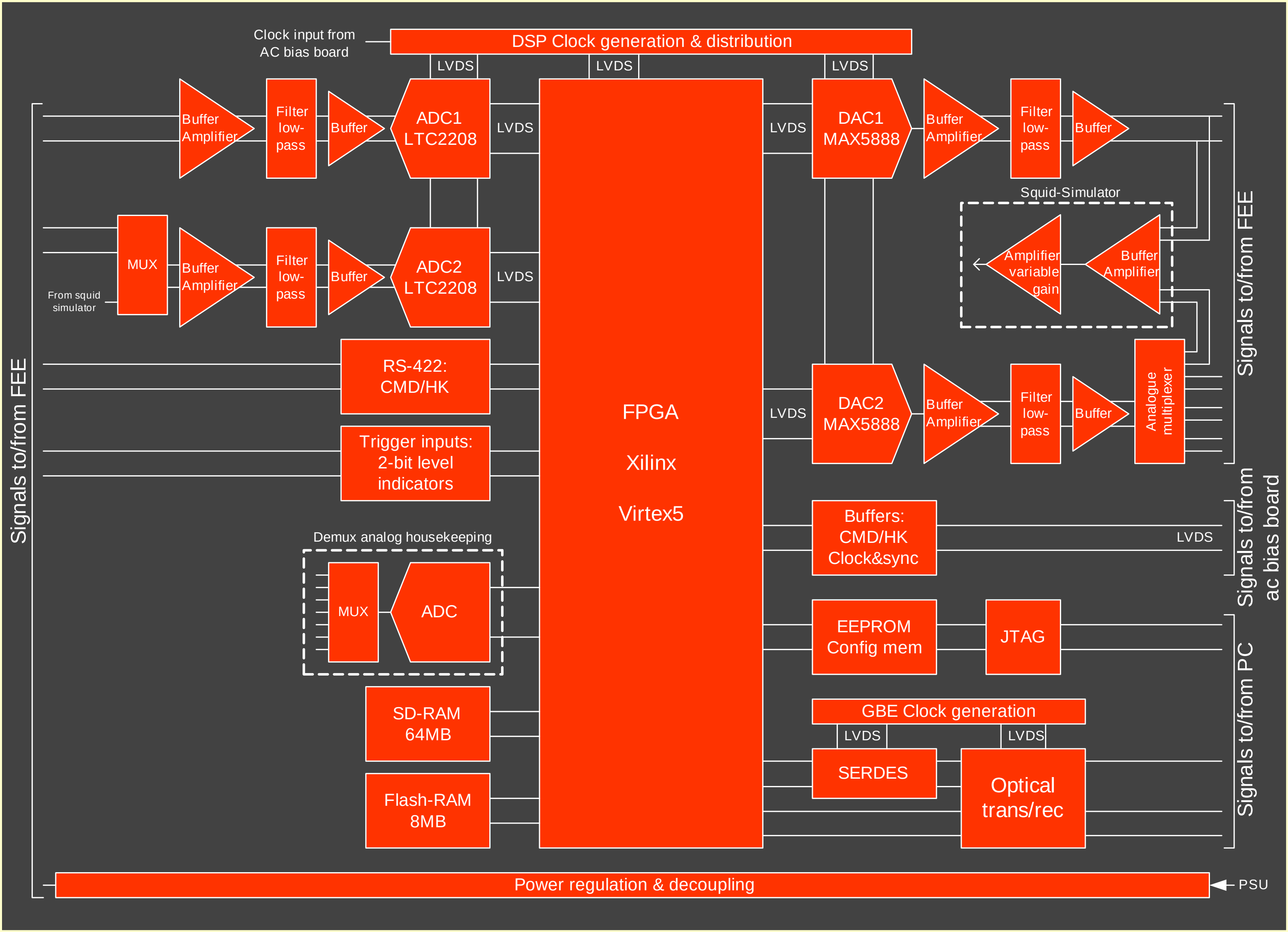
- Blue error signal at SQUID input for BBFB with a GBW = 32 kHz
  - error signal amplitude scales with $1/\tau_{rise}$



Linear time axis showing also the 2^{nd} order harmonic for $k_2/k_1 = 1$

The 2^{nd} order contribution in this case equals 7 10^{-3}

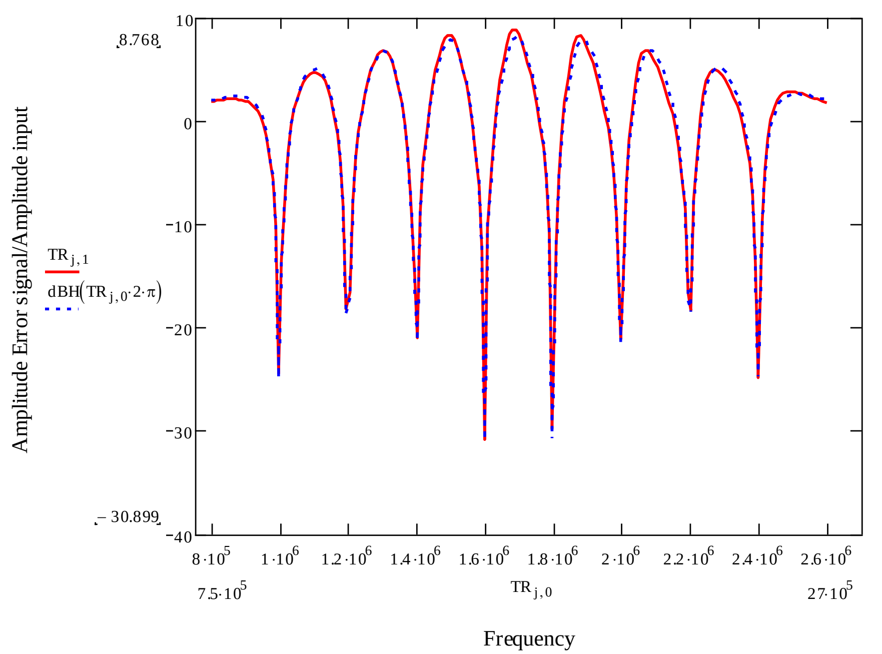
BaseBand Feedback Electronics board

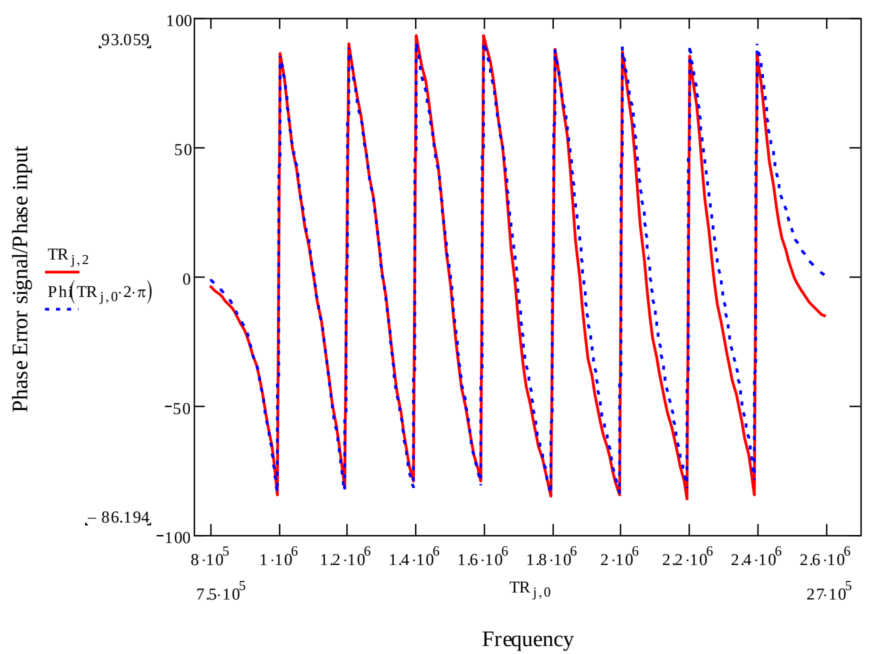


SRON

Amplitude and Phase (error signal/input signal) for 8 channels with BBFB

Red lines: Data from a commercial Xylinx breadboard
Blue lines: Model





Amplitude: red-data blue-model Phase: red-data blue-model

Gain-bandwidth of 35 kHz for 200 kHz spacing and 830 ns delay

FLL-gain of 2x at highest signal frequency (16 kHz)

2. Measurements

4. TP generated by DeMux board; TES normal
   367 kHz carrier generated by DeMUX board
   Baseband feedback by DeMux board
   Digitization and demodulation via DeMUX board

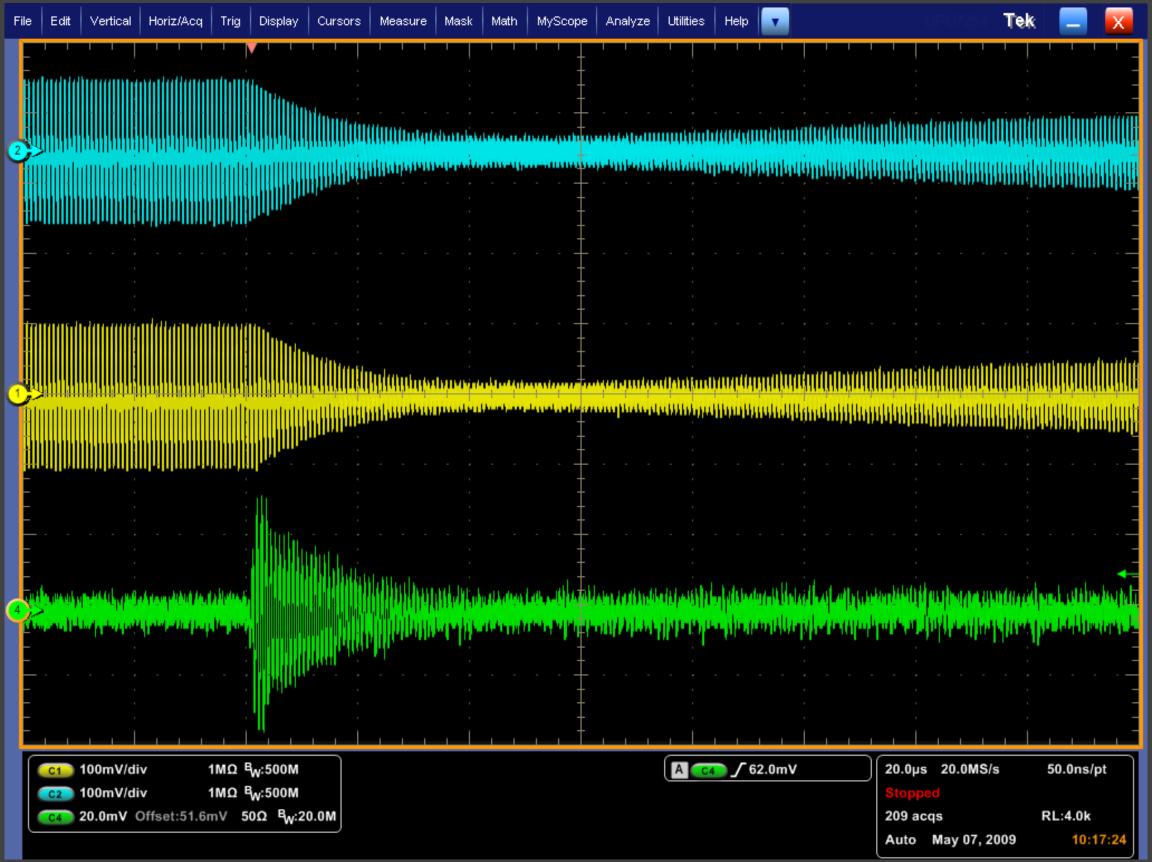
Closure demonstrated at 367 kHz and 1 MHz

Loop gain = 18
GBW = 300 kHz

Carrier + tailpulse

Feedback signal
(de- & remodulated)

Error signal x 25

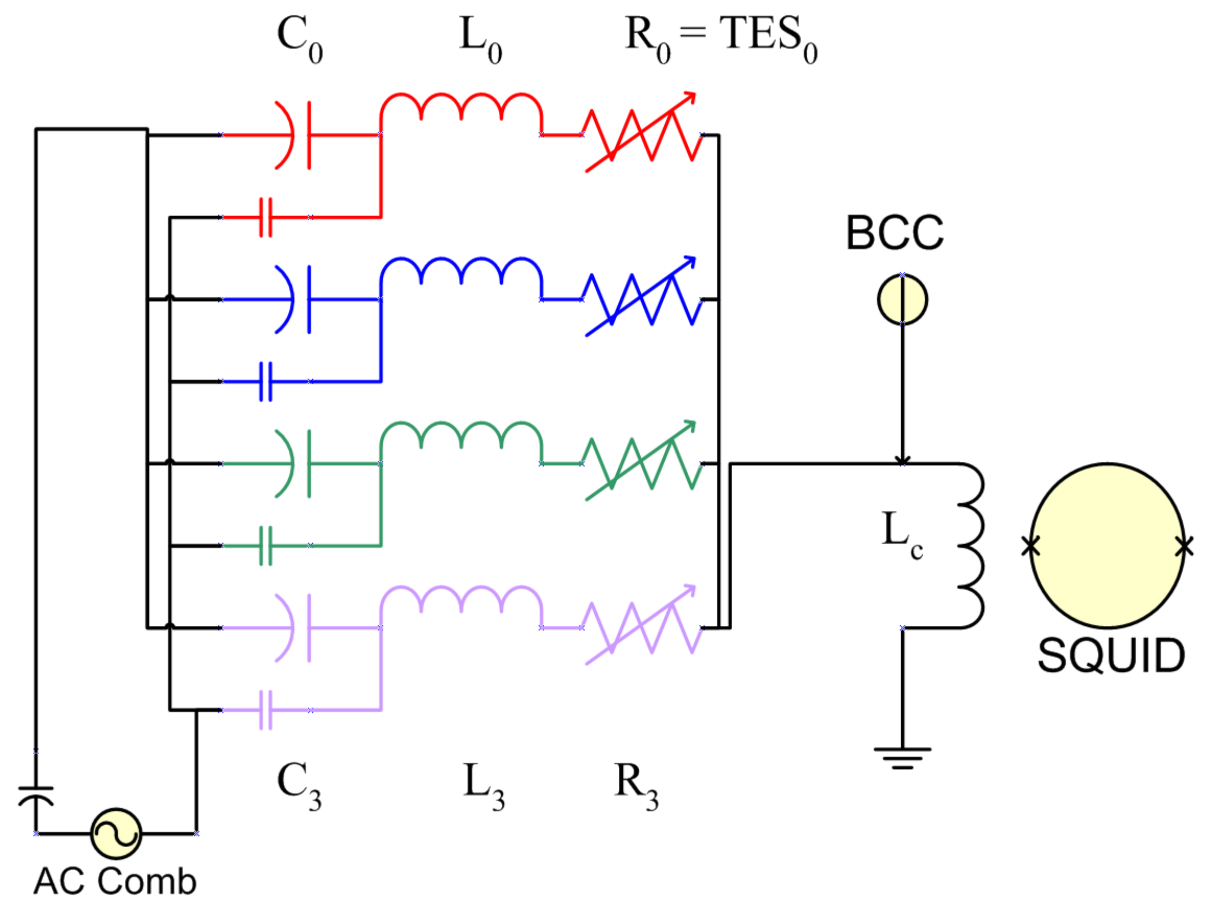


C1 100mV/div 1MΩ B_W:500M
C2 100mV/div 1MΩ B_W:500M
C4 20.0mV Offset:51.6mV 50Ω B_W:20.0M

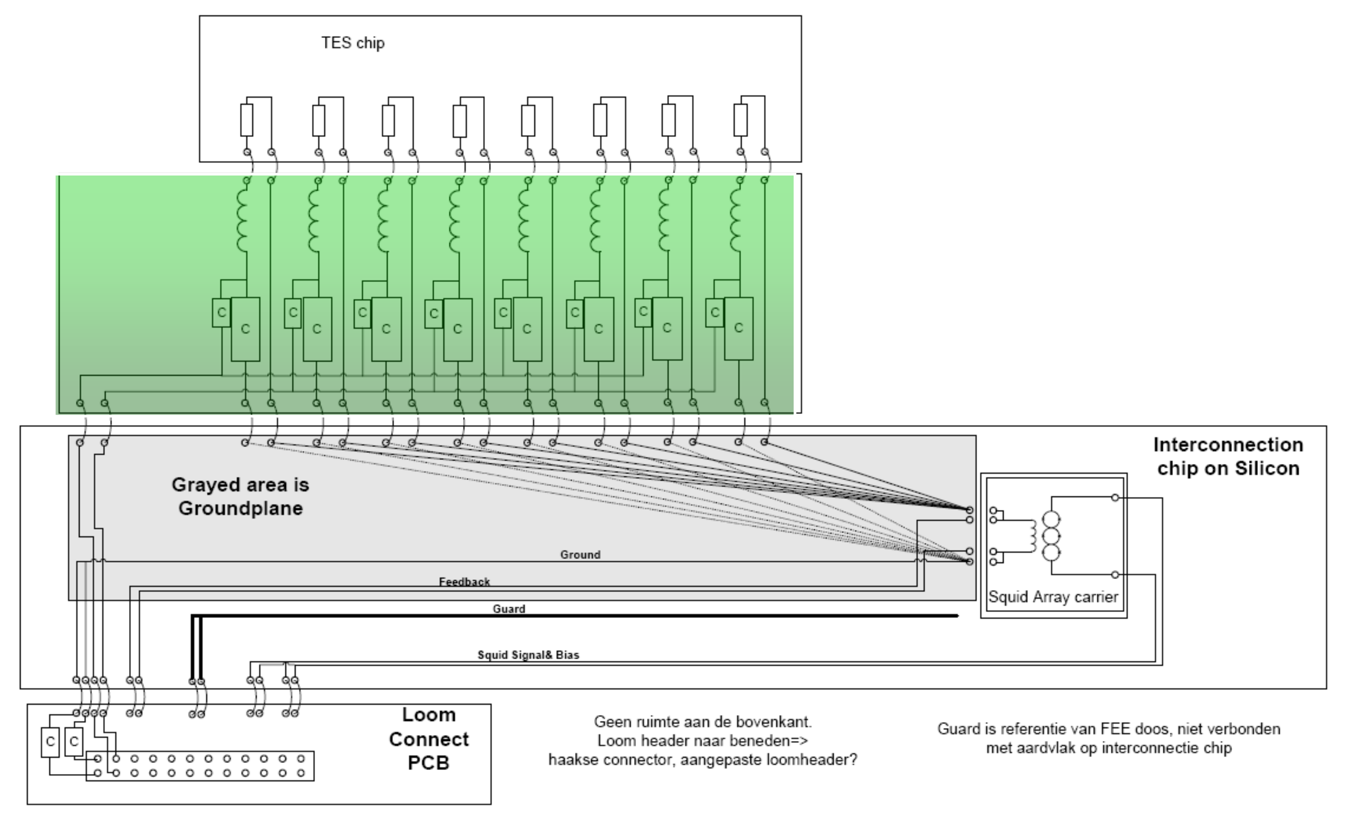
A C4 ⎍ 62.0mV

20.0µs 20.0MS/s 50.0ns/pt
Stopped
209 acqs RL:4.0k
Auto May 07, 2009 10:17:24

LC-filters circuit & implementation



LC-filters circuit & implementation

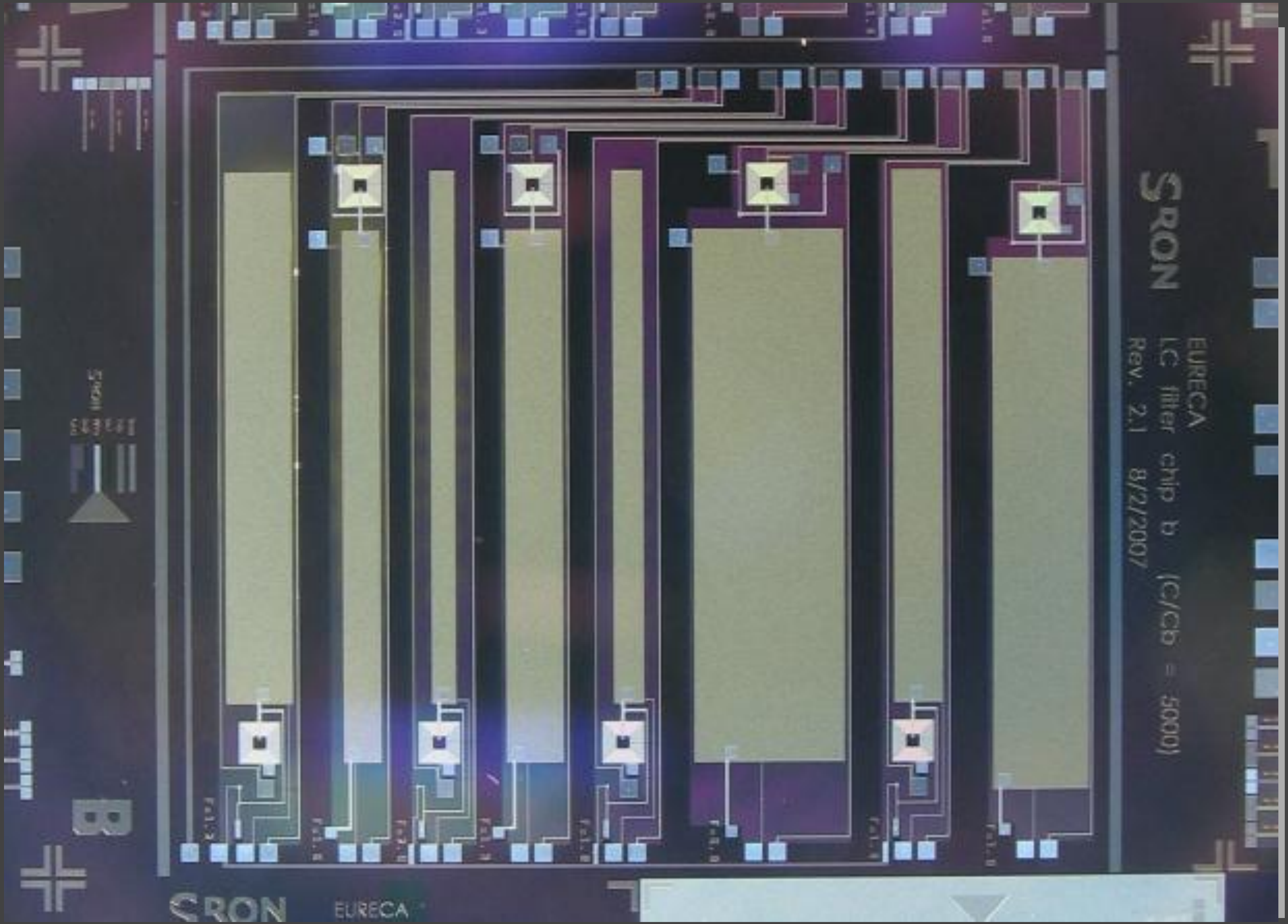


Geen ruimte aan de bovenkant.
Loom header naar beneden=>
haakse connector, aangepaste loomheader?

Guard is referentie van FEE doos, niet verbonden
met aardvlak op interconnectie chip

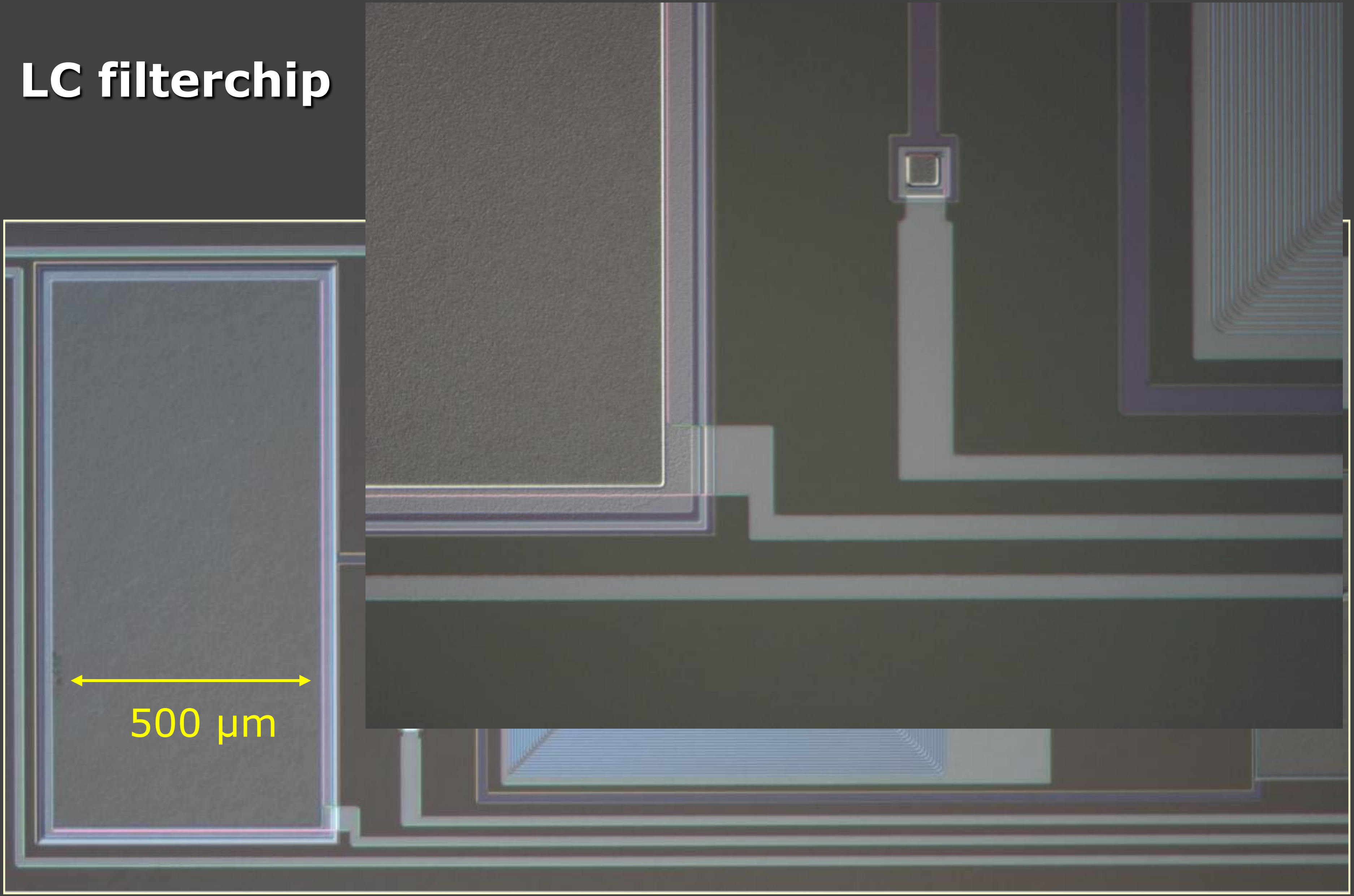
Figure 2. Electrical scheme for the bias and signal chain of the first Eureca channel. The components for each TES chain are laid-out in parallel lanes as much as possible.

8 channel LC chip design



20 x 14 mm^2

LC filterchip



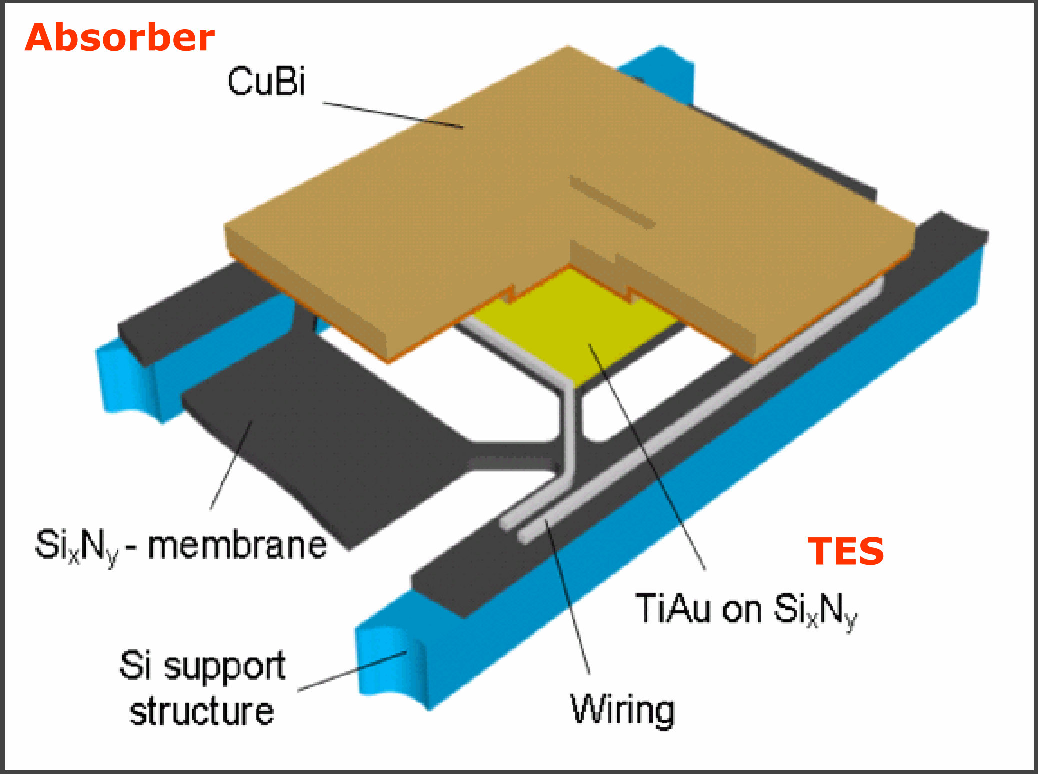
Contents on fabrication

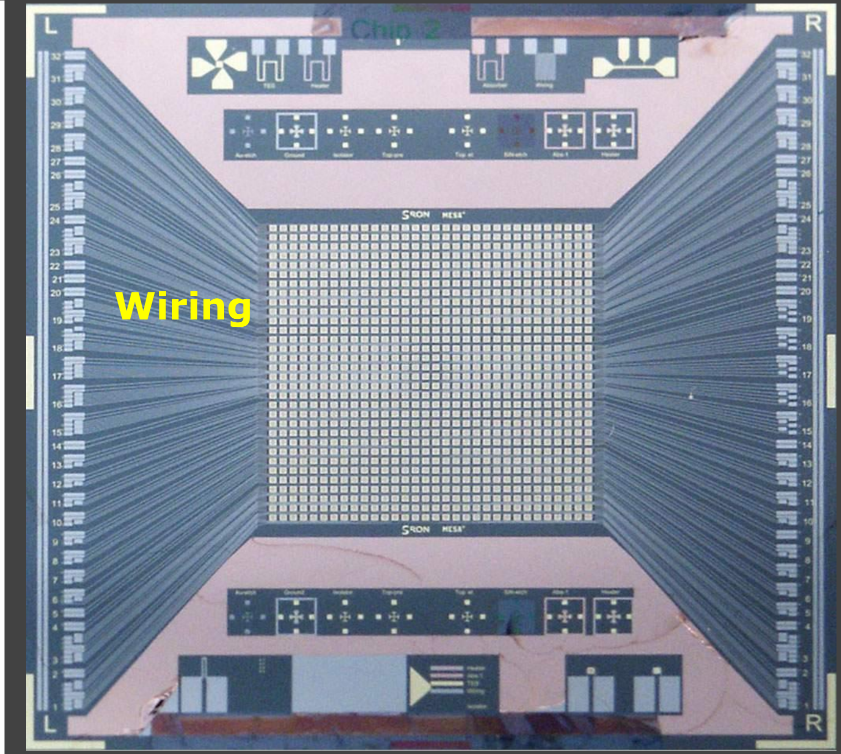
- Pixel components
  - Micro-mechanic support structure
  - TES or Transition Edge Thermometer
  - Absorber
  - Wiring
  - Pixel release
  - Cooling

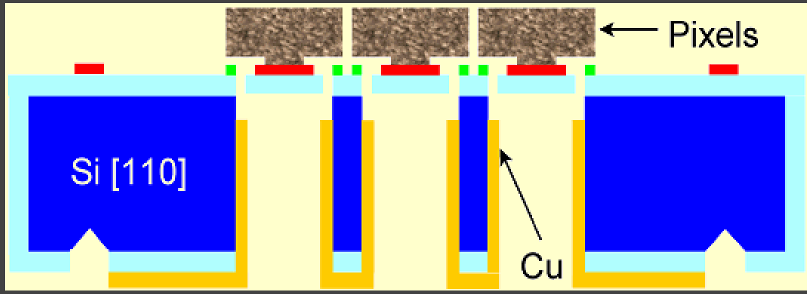
- Pixel optimization:
  - Trials for steepness/excess noise
  - Avoiding strain concentrations

- Open issues
- Space qualification
- Facilities

Calorimeter pixel components



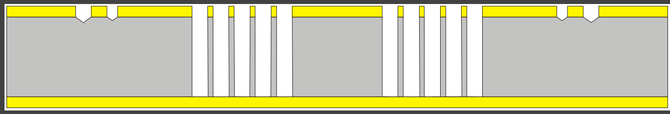




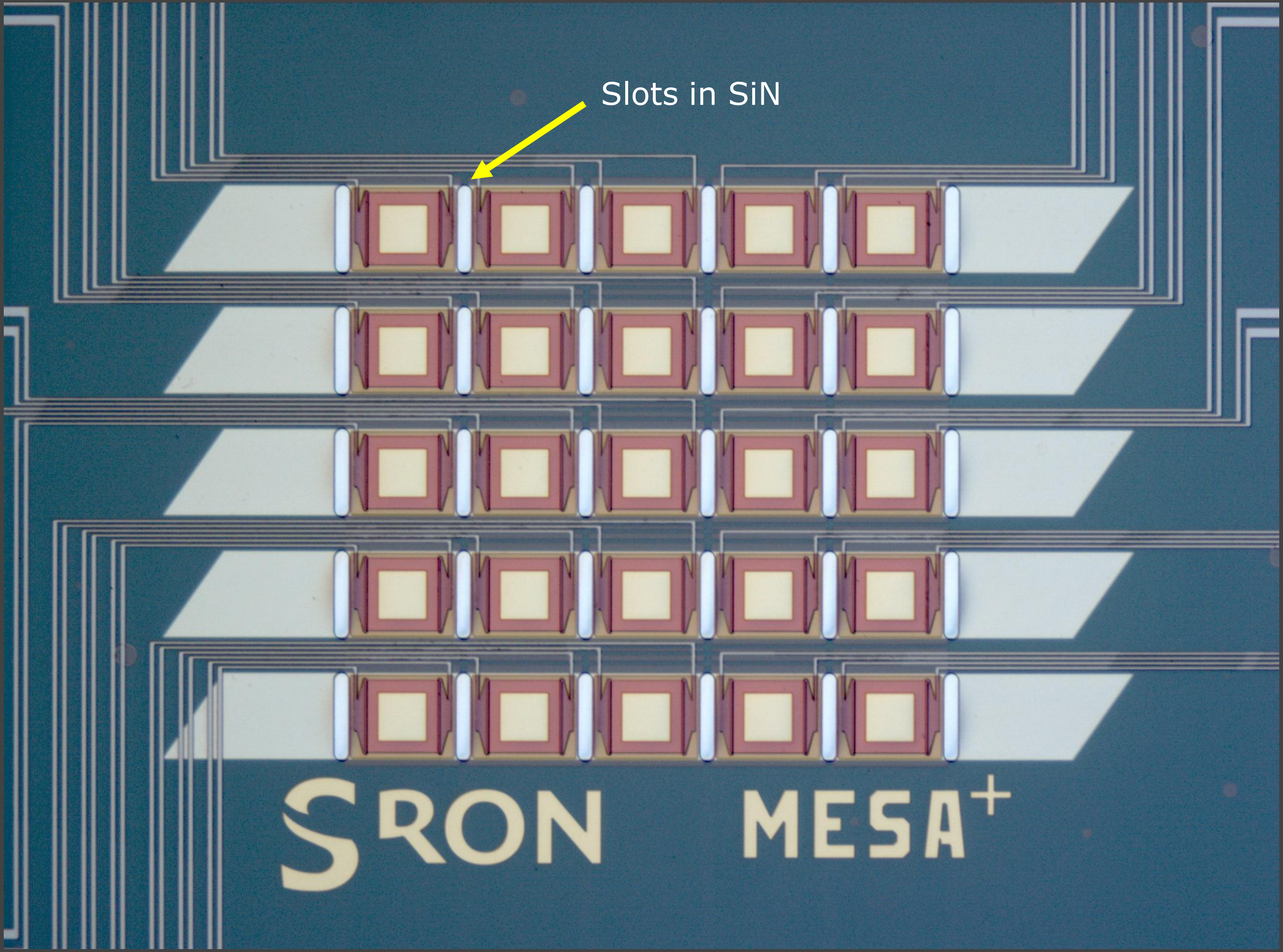
Cooling

Micromechanical support structure

- Fabrication steps:
    - Wafer cleaning Si [110]
    - LPCVD SixNy coating @ MESA TuE
    - Vangbo alignment pattern (back side)
        - Etching SiN
        - Short KOH etch
    - Slotted pattern (back side)
        - Etching SiN
        - Long KOH etch (full wafer depth)
    - (metal processing)
    - Membrane pattern



5x5 array before absorber and release



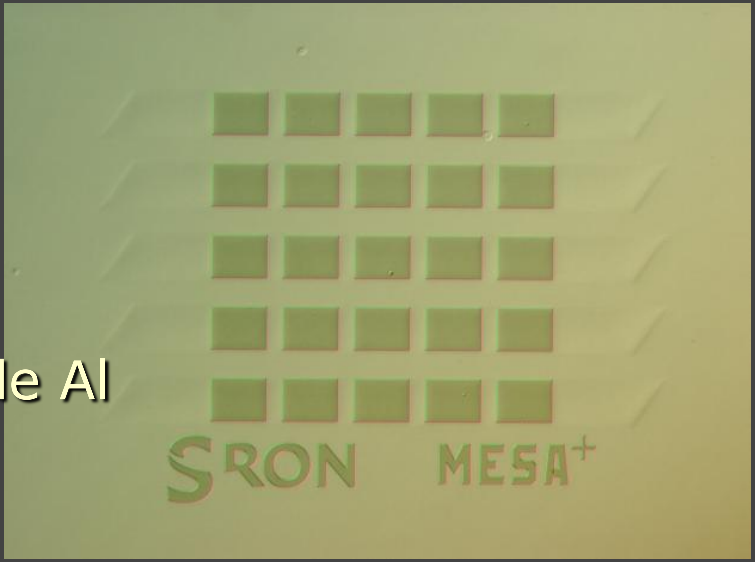
TES – Transition Edge Thermometer

Process:

- Sputtercoating of cooling layer (Al) on back side
- Evaporation of Ti/Au/Ti on front side
- Lithography of TES pattern, alignment to back side
- Wet etching
  - Ti: diluted HF
  - Au: I_2/KI, rinse in $Na_2S_2O_3$

Critical issues:

- Wafer handling, protection of backside Al
- Ti/Au deposition (next page)



Ti/Au deposition

- Tc of bi-layer is very sensitive to:
  - Thicknesses
  - Interface condition
  - Purity
  - Temperature > ~100 C

- Approach:
  - Avoid the use of “dirty” materials in the system
  - Clean vacuum
  - Automated deposition sequence with very short delay between Ti and Au (< 2 sec) and reproducible growth rate
  - Cooling of layers on membranes
  - Calibration runs before calorimeter fab.
  - Process accuracy T_c +/- 15 mK

On-chip wiring

- Wiring issues become especially important for large arrays:
  - Pitch on limited space between pixel rows
  - Yield (shorts & interruptions)
  - Inductance (should be low compared to main FDM inductance)
  - Cross-talk
  - Critical current

- 4 cases were studied:

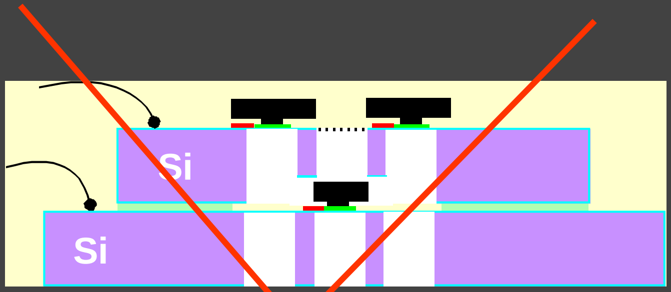
  a) (Multi-layer) wiring on the support bars

  b) Double wafer array

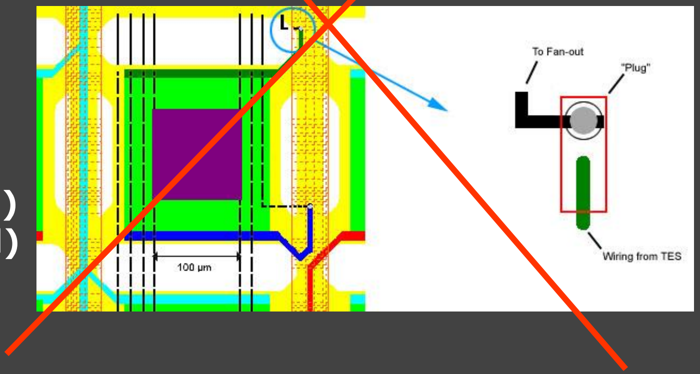
  c) Wiring under pixel (surface micro-machining)

  d) Wiring through the wafer

b)

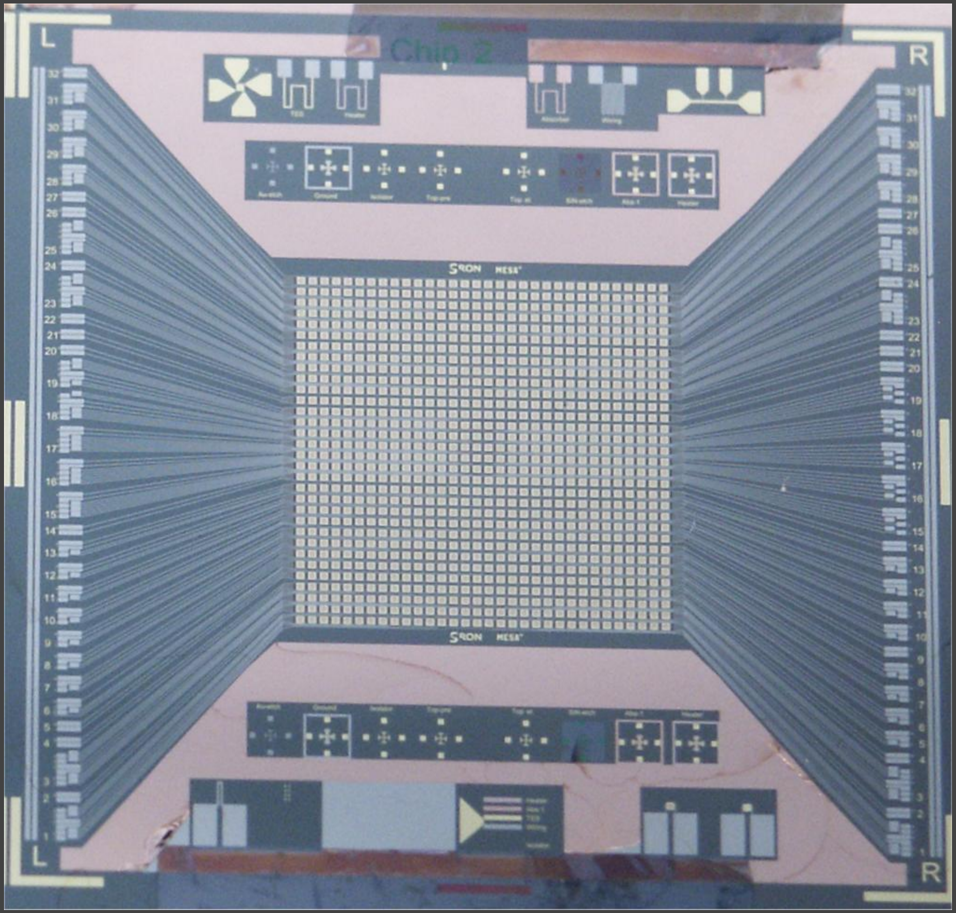


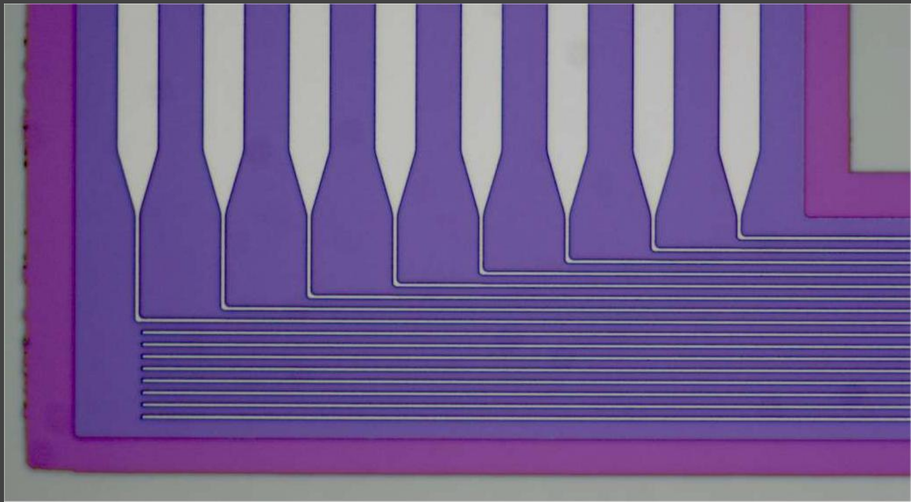
c)
d)



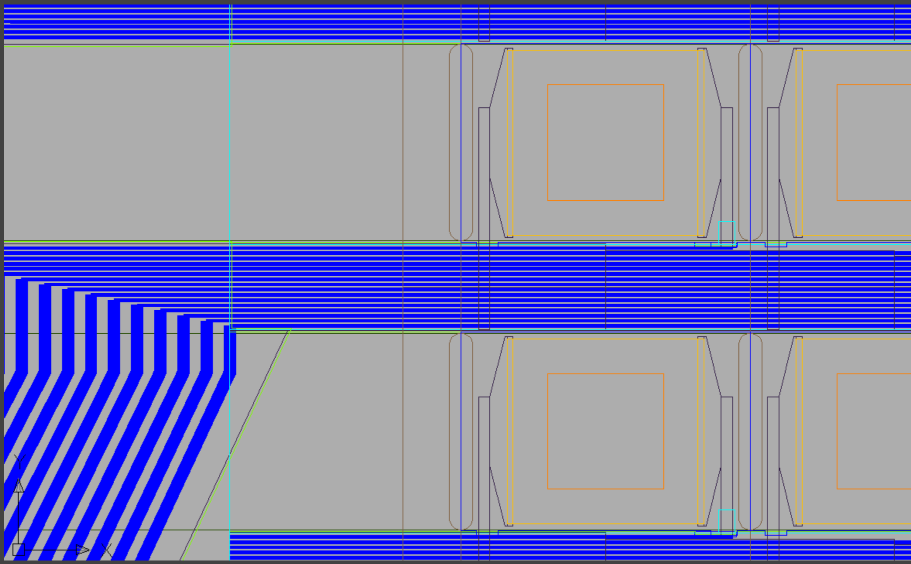
Present choice: case a) seems feasible for 1 kpixel array with ~ 70 µm beams

Wiring: Prototype 32 x 32 pixel Array

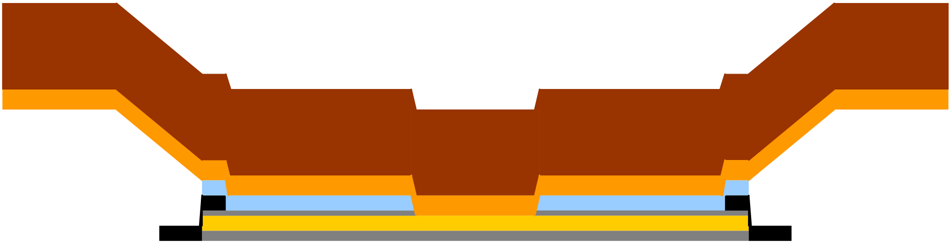




16 lines on ground plane, pitch 2.8 µm



Absorber fabrication

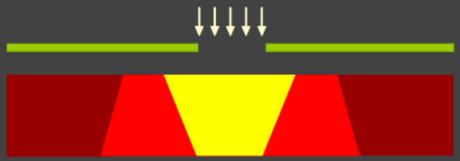


Schematic sideview of pixel with overhanging absorber

Formation of photoresist mould

First exposure using an inverted mask, the exposed areas (outside the "hat" pattern) finally remain.

Reversal bake, 2 min on 130 °C cross-links the exposed area while the unexposed area remains photo-active.

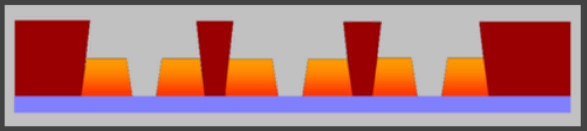


Second exposure of the "foot print" in proximity mode to create positive slope. The exposure dose is to generate a high development rate of the exposed (yellow) resist.

Third exposure is a flood exposure, Exposure dose is low to create selective development rate of the "hat" pattern with respect to the "foot" pattern (yellow).

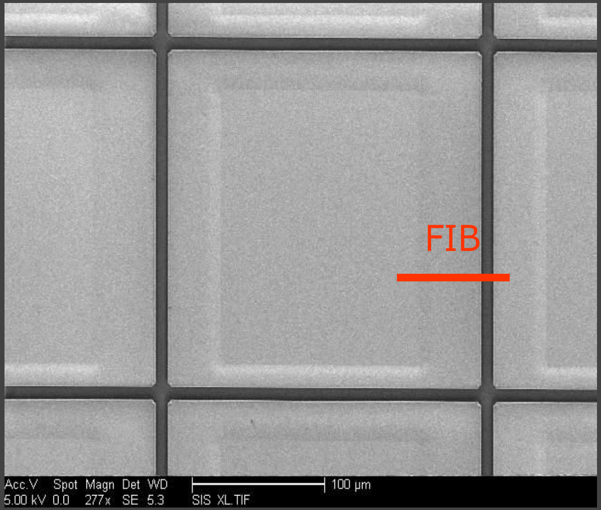
Development of the mushroom shaped mould, the development time is a parameter to adjust the height of the remaining resist which determines the distance between free-hanging absorber hat and the substrate.

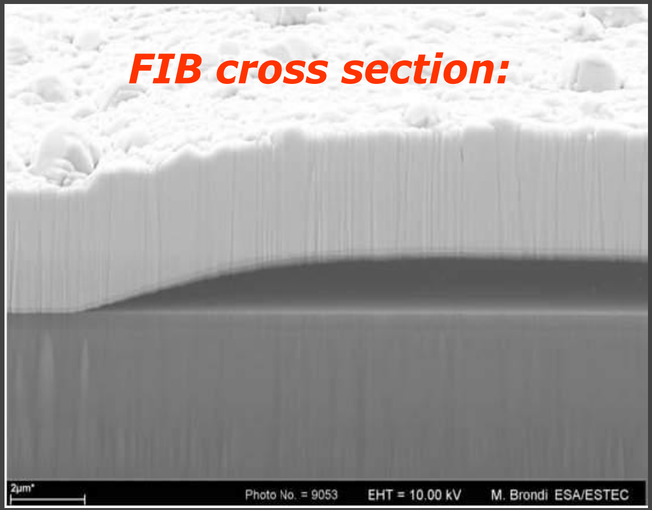
Array:

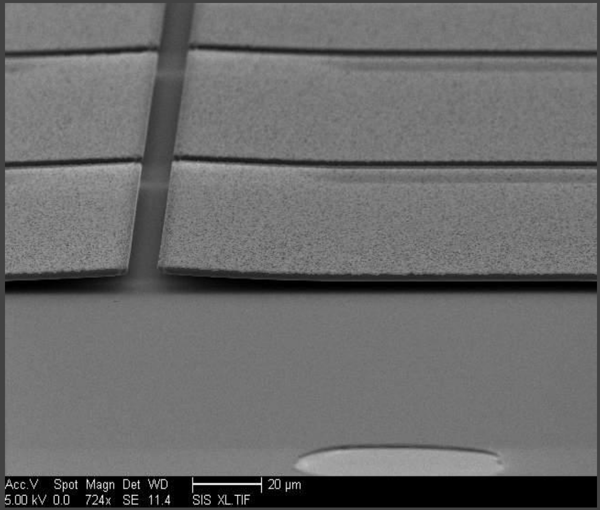


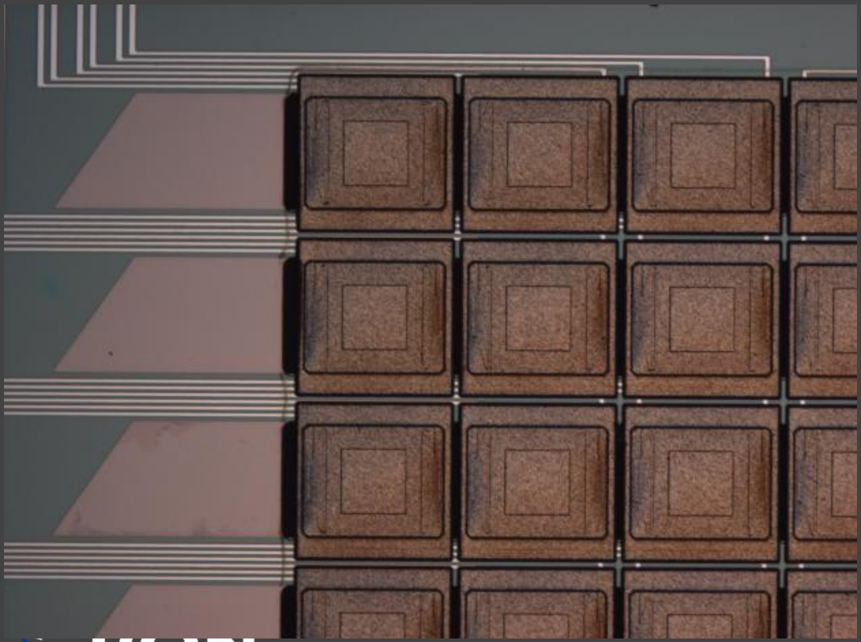
The negative-sloped resist forms the lateral distance between the absorbers hats.

Absorber fabrication









SEM micrographs of mushroom shaped Cu/Bi absorbers.

Upper left: Top view of array on solid Si.
Red line: FIB sectioning.
Upper right: 70º tilted view, showing bending.
Left: Process on membrane pixels.

Pixel size is 250x250 µm2. Filling factor = 93%.

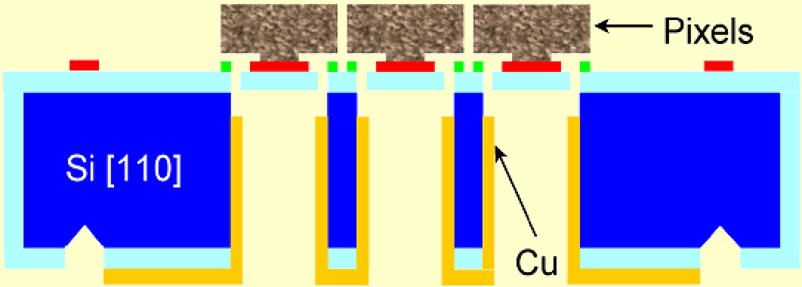
Present Ti/Cu/Bi thickness: 5/150/3000 nm:
Good X-ray performance

Pixel release

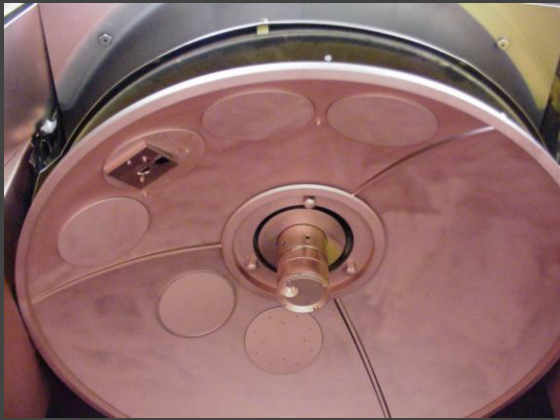
- ……..
- RIE etching of SiN
- Resist removal
- Absorber pattern & deposition
- Front side resist coating
- Back side Al etch
- Lift-off (few hours)
- Rinsing
- Drying (face down in oven)

❖ Tricky handling
❖ Avoid loss of Cu below Bi
❖ Avoid sticking of absorber to substrate

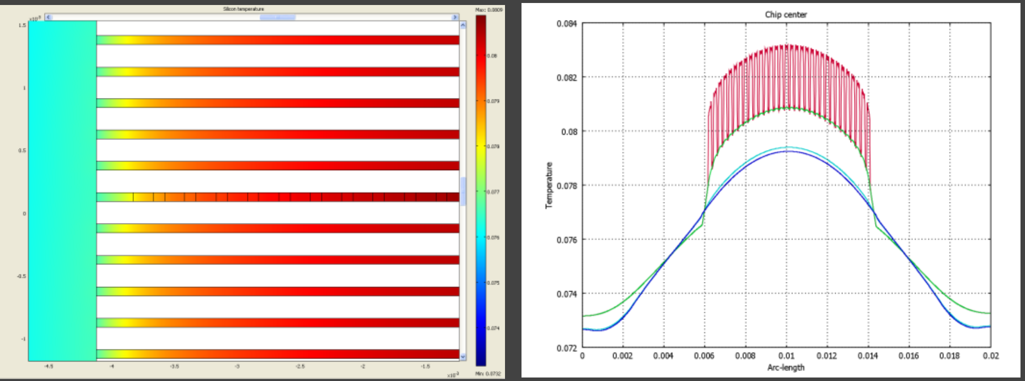
Cooling



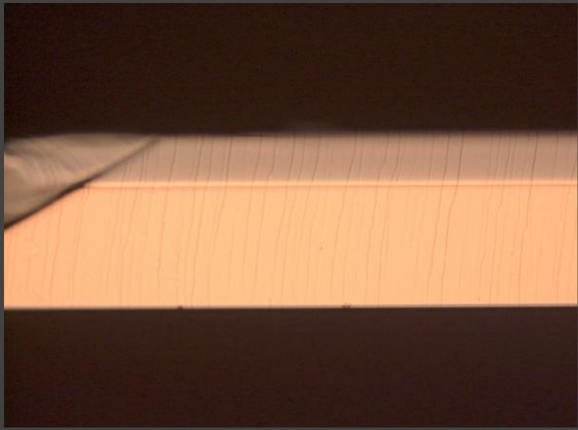
- Heat conduction of Si beams insufficient for bias power removal
- Cu is shadow evaporated onto sides of the beams and back side of chip
- Simulations and experiments confirm vastly improved conduction
- Thermal cross talk is reduced



Adjustable angle in evaporator



FEM simulations

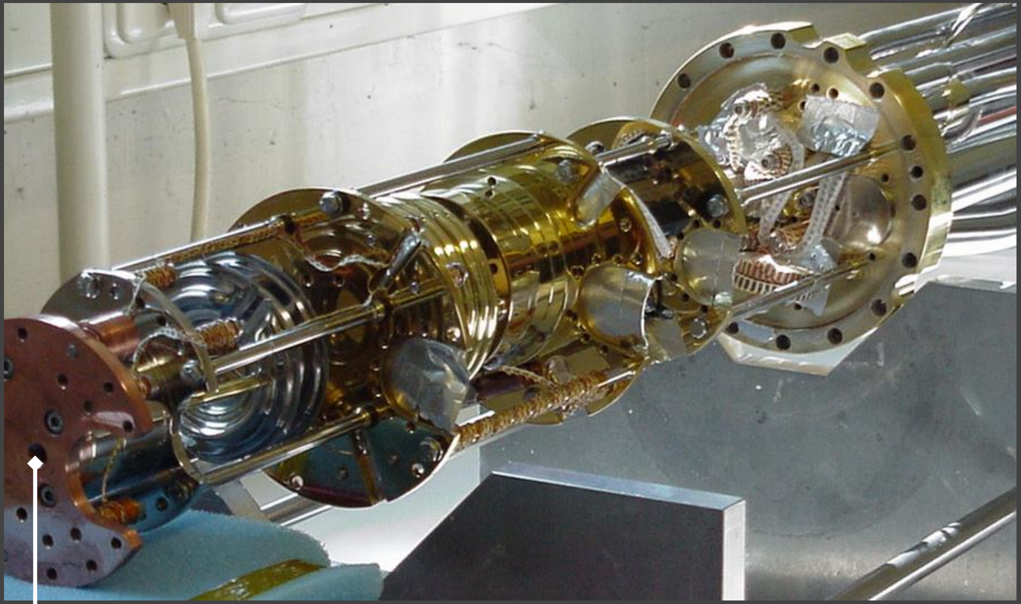


Side view on (broken) beam

Setup’s for single pixel characterization

Kelvinox dilution fridge

the insert

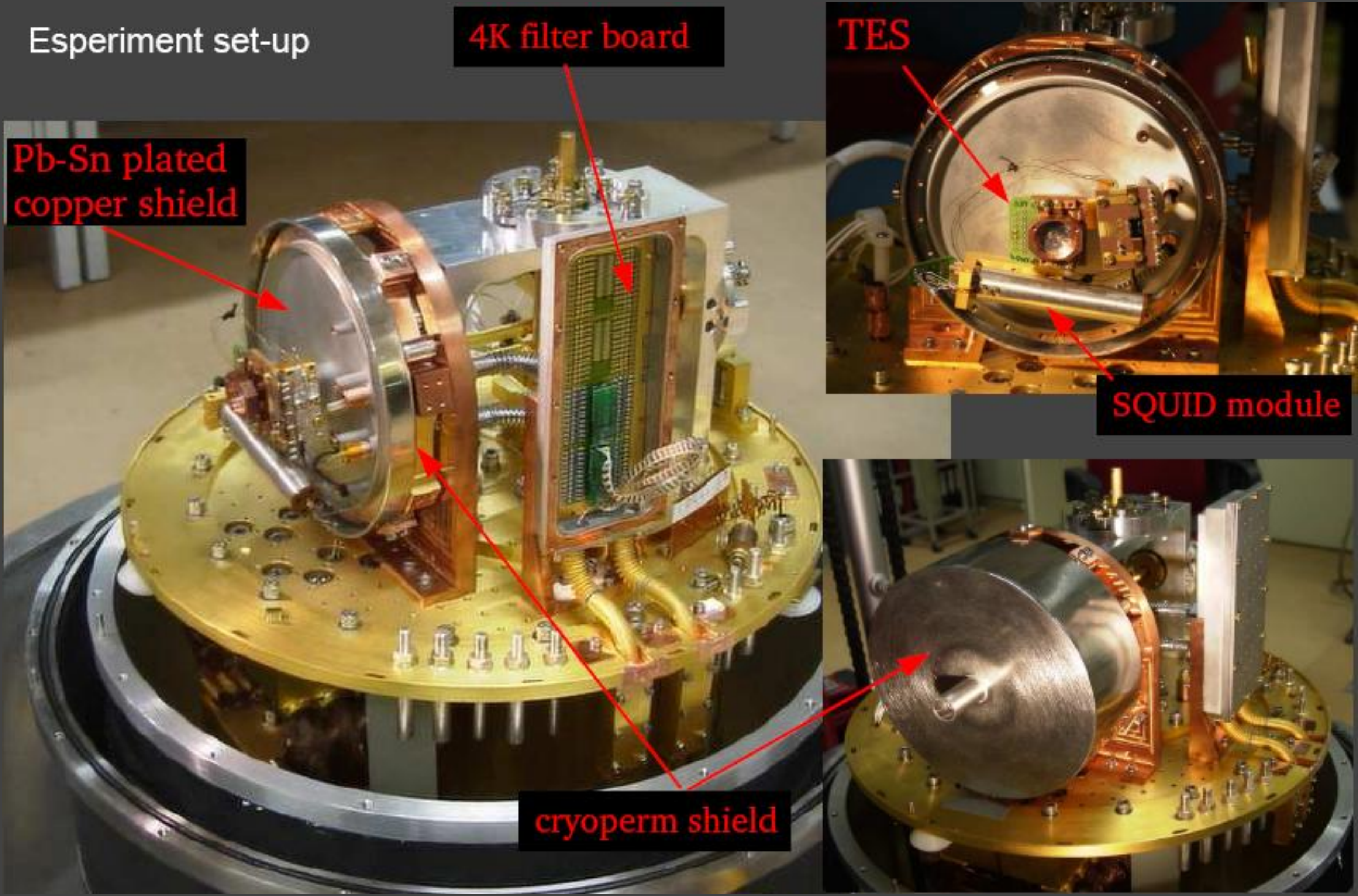


mounting position for bracket with samples

For the moment FDM takes only place in ADR

EMC/GROUNDING/HARNESS/FILTERING

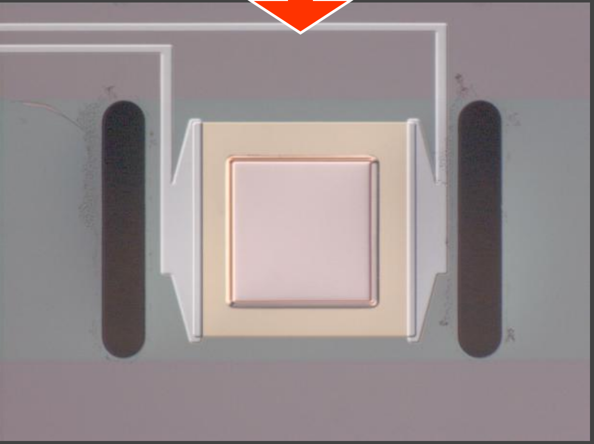
Esperiment set-up



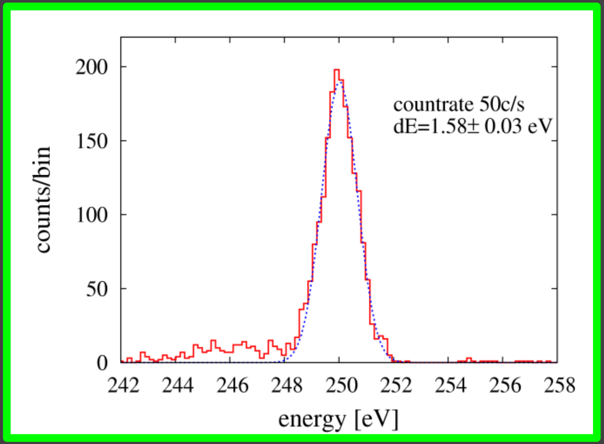
Narrow Field Imager - TES-based Micro-Calorimeter

PERFORMANCE for PIXELS from 5 x 5 arrays

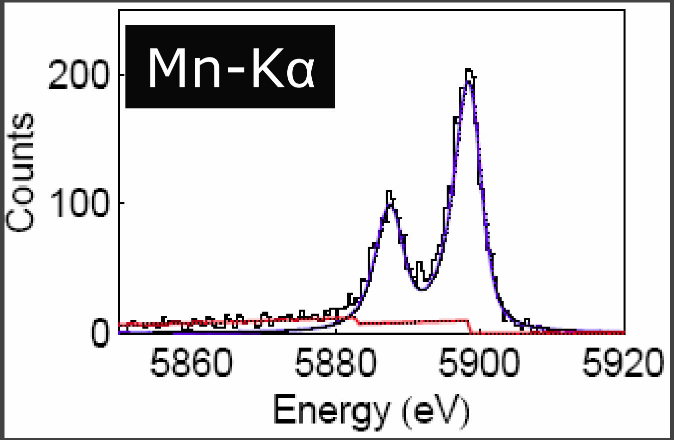
$\Delta E_{TDL} \approx 3.1$ eV



Cu-absorber



$\Delta E = 1.6$ eV @ 250eV

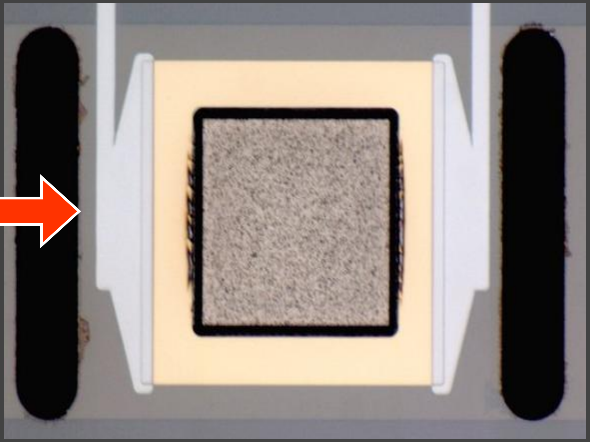


$\Delta E = 2.9$ eV at 5.9 keV

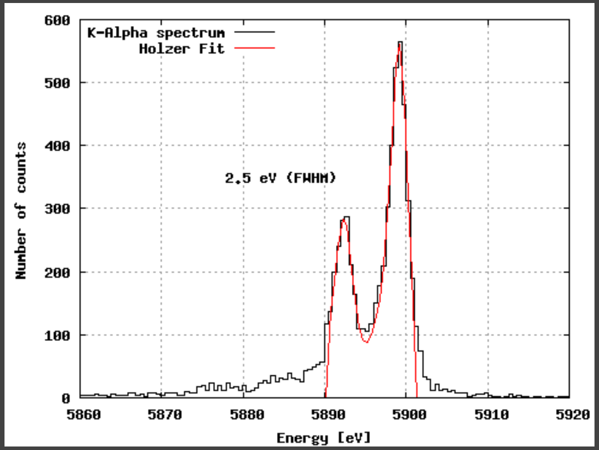
100 µs fall time

$\Delta E_{TDL} \approx 3.8$ eV

$$\Delta E_{TDL} = 2.35\sqrt{k_B T^2 C}$$



Cu/Bi-absorber



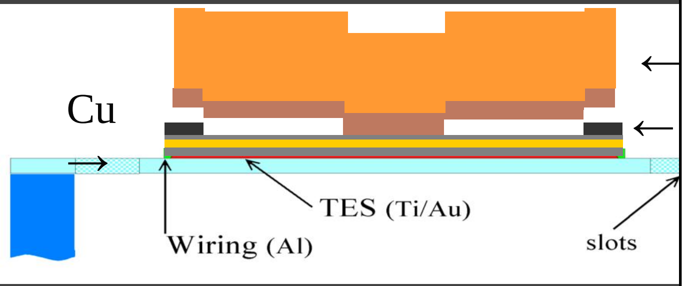
$\Delta E = 2.5$ eV @ 5.9 keV

Narrow Field Imager - TES-based Micro-Calorimeter

PERFORMANCE for PIXELS from 5 x 5 arrays

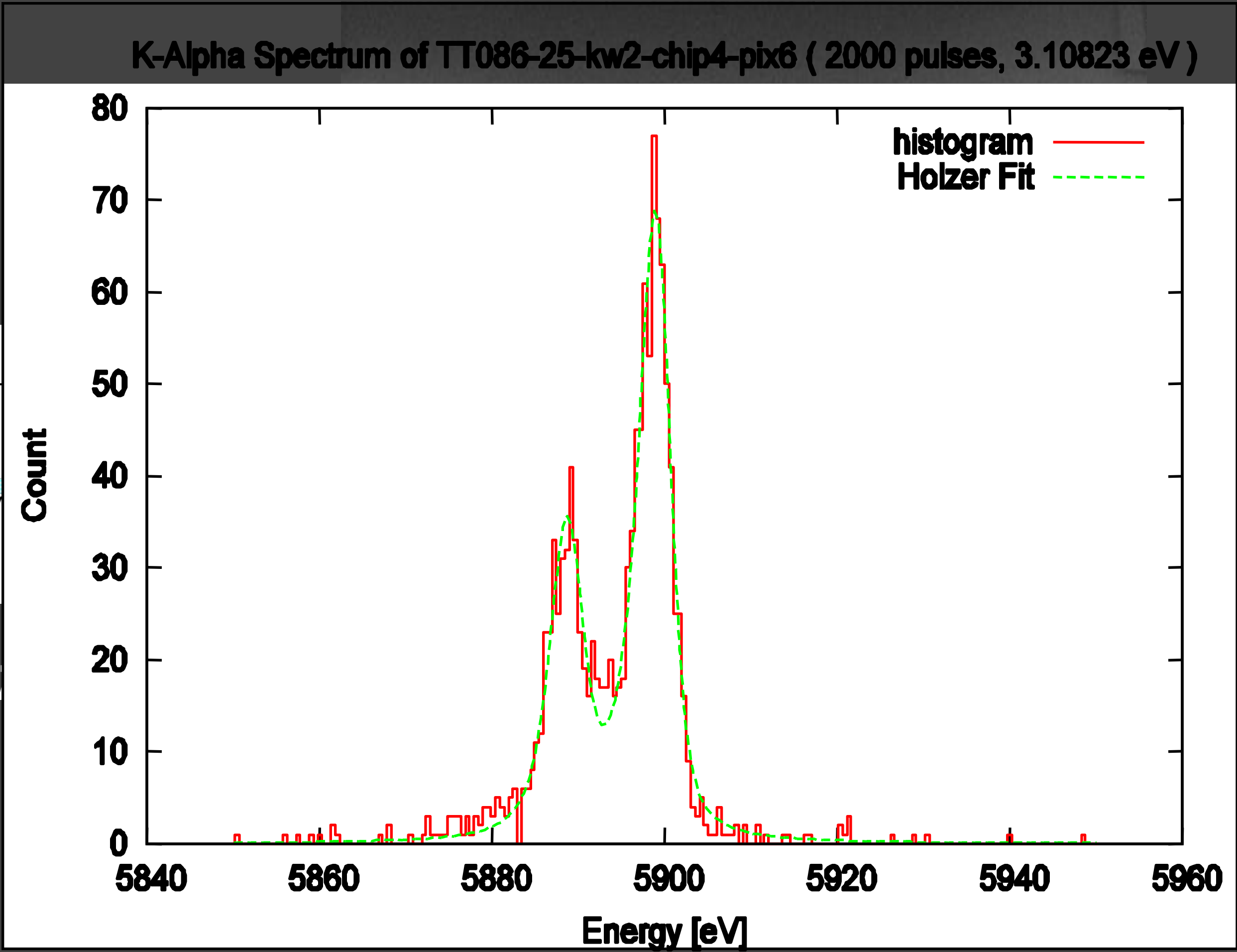
$$\Delta E_{TDL} = 2.35\sqrt{k_B T^2 C}$$

$\Delta E_{TDL} \approx 4.4$ eV



Cu/Bi-absorber (0.3/3 μm)

T_C = 116 mK



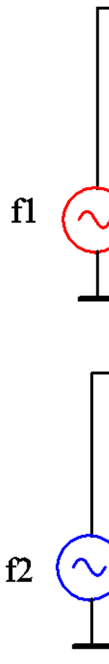
K-Alpha Spectrum of TT086-25-kw2-chip4-pix6 (2000 pulses, 3.10823 eV)

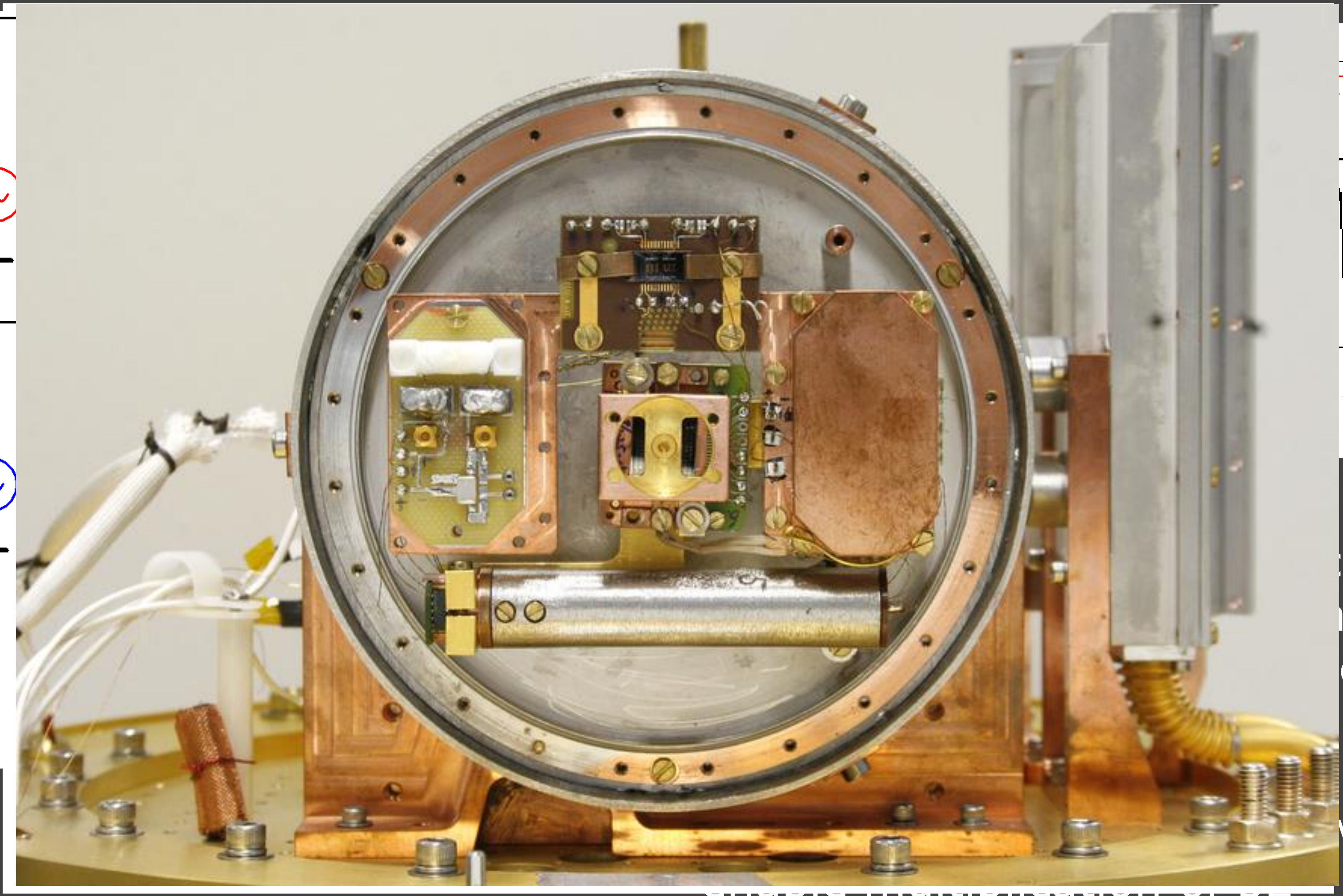
ΔE = 3.1 eV @ 5.9 keV

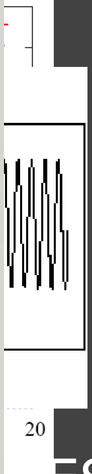
200 μs fall time

SRON

FREQUENCY DOMAIN MULTIPLEXING CURRENT SUMMING TOPOLOGY







cts

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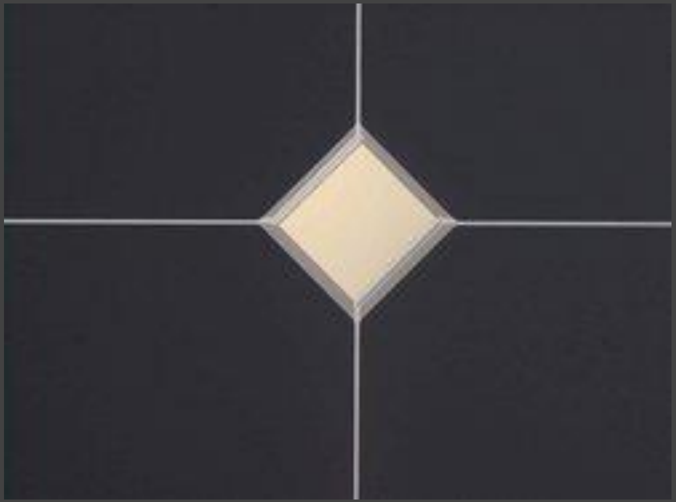
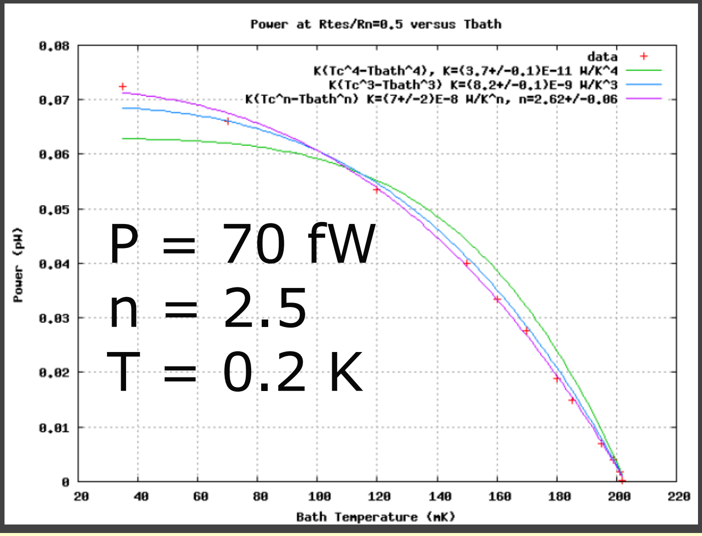
enable multiplication of 32 45
pixels/channel

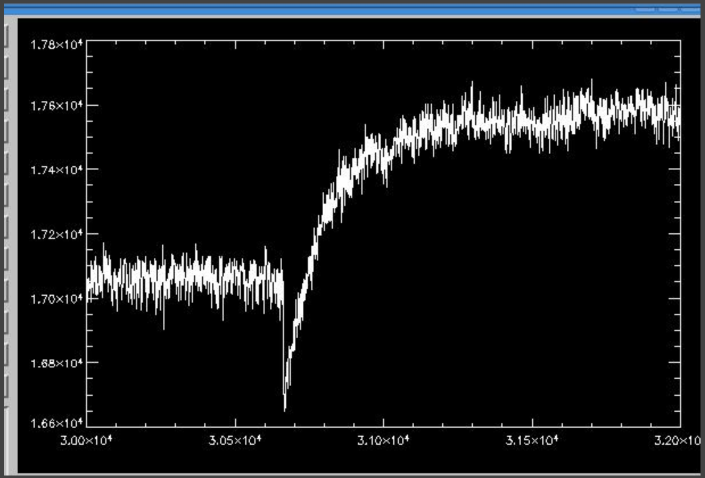
Low NEP TES for SAFARI/SPICA





P = 70 fW
n = 2.5
T = 0.2 K

$$NEP = \sqrt{4kT^2P} \approx \sqrt{4kTP}$$



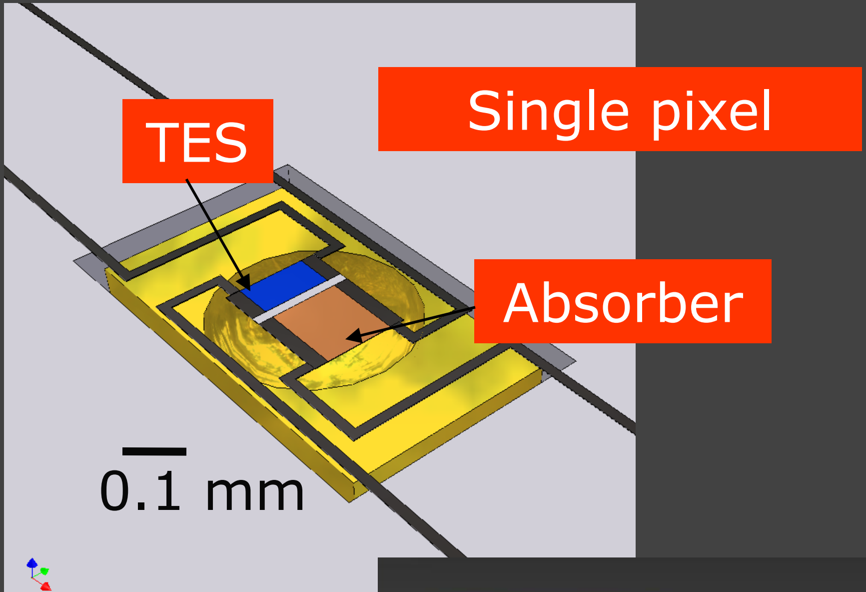
T_C = 200 mK
100 x 100 μm TES
4 legs of 5 μm and 1.8 mm

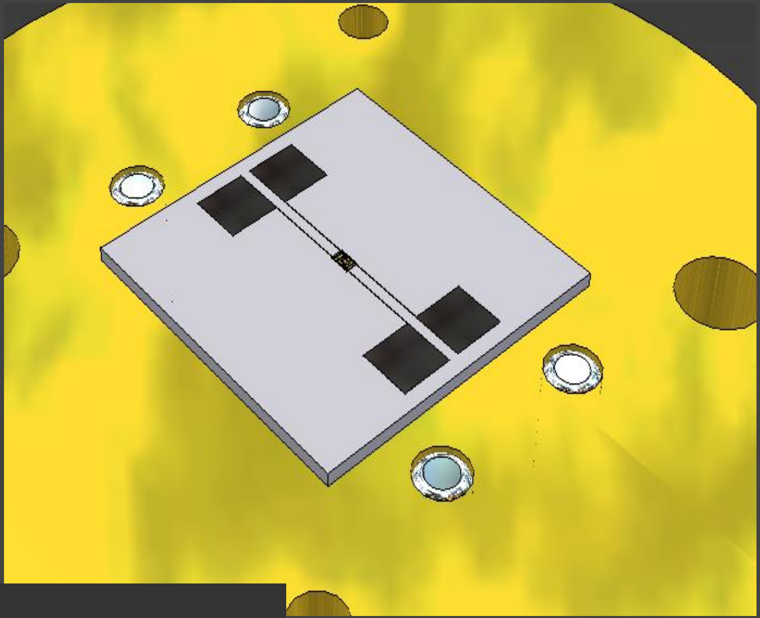
Measured
P = 70 fW
NEP = 10^{-18} W/√Hz
τ_{eff} = 0.2 ms

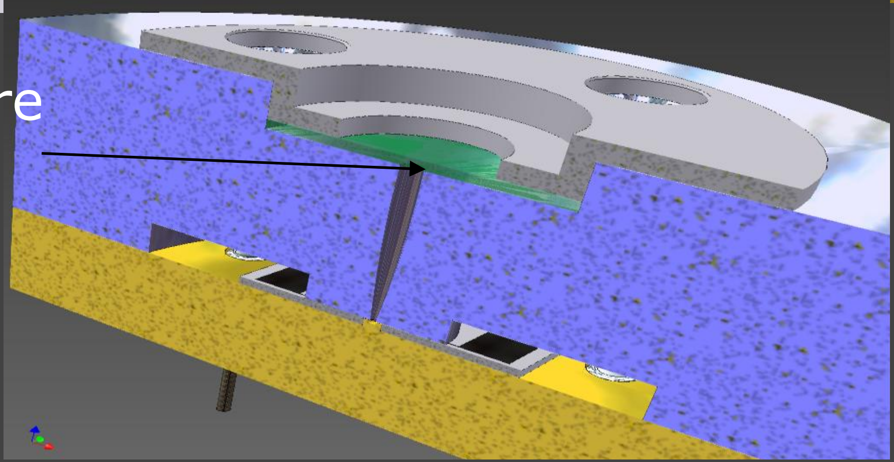
Next steps:

T → 100 mK
Leg width → 2 μm

Single optical pixel design (short wavelength channel is most difficult)



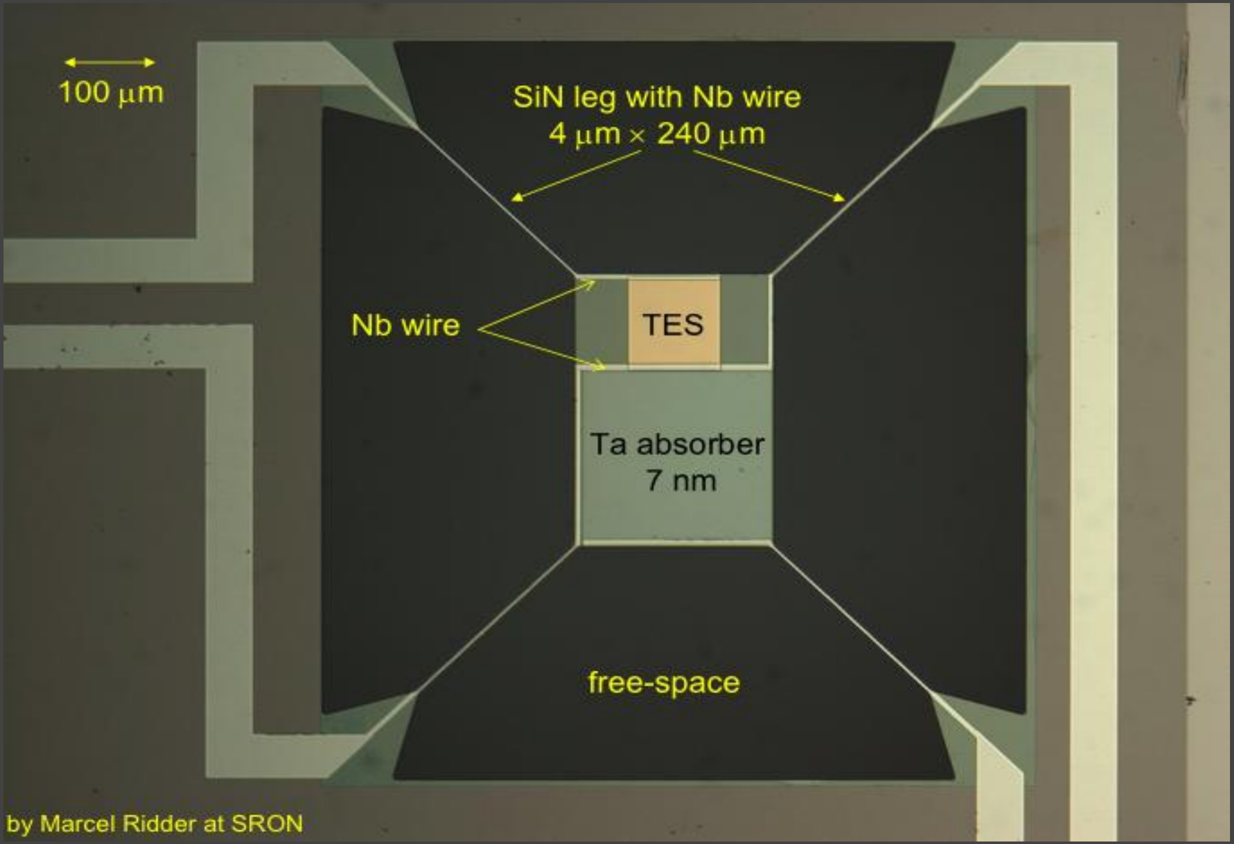




Horn aperture is 450 μm

Example: 11 mm test chip size

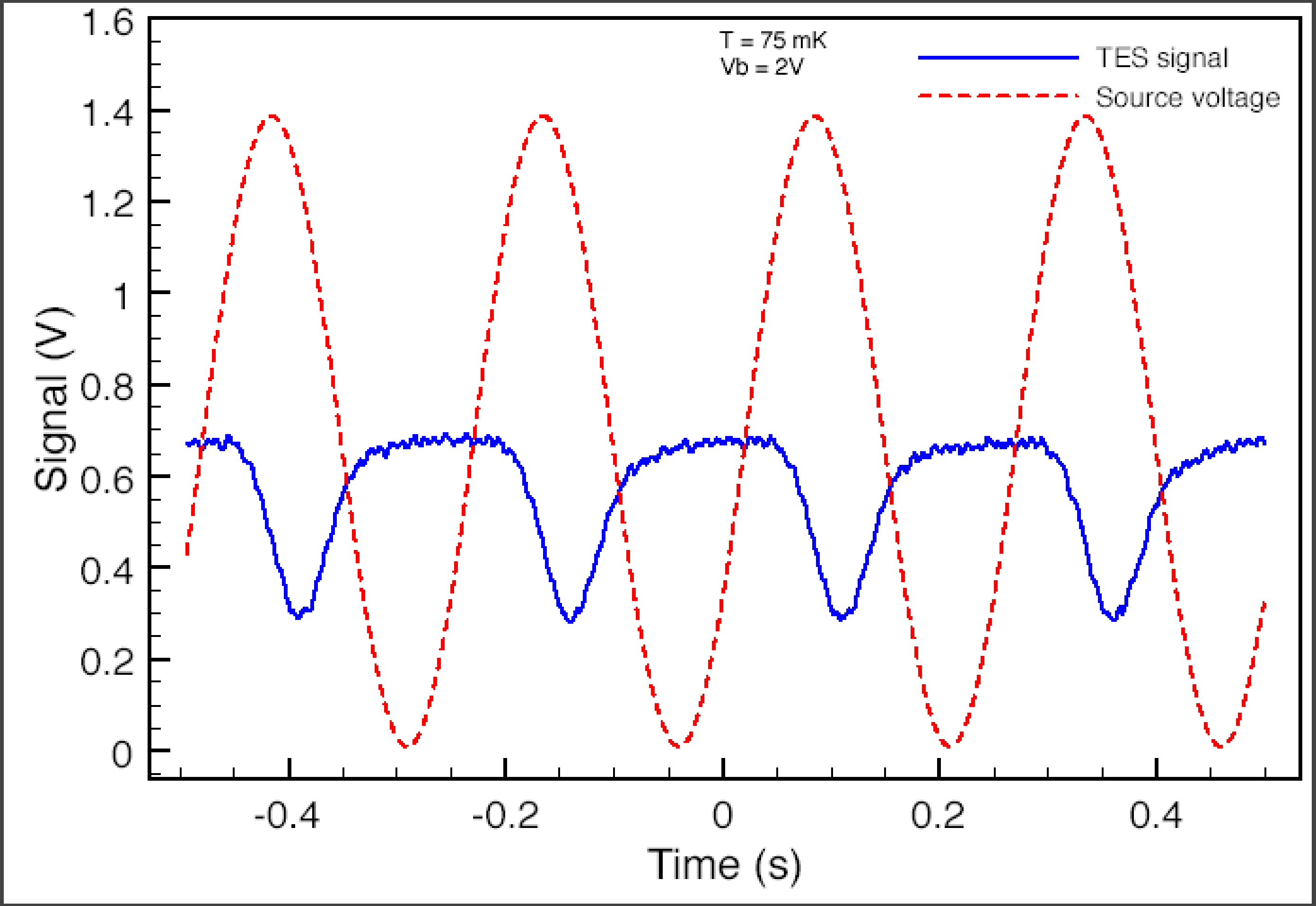
Single pixel with optical absorber (a real picture)



by Marcel Ridder at SRON

Free space 400 Ohms per square absorber coupled to TES
First devices fabricated and undergoing dark testing
Optical testing ready to begin

It works!!!



Absorbers fed by circular horn antennas
Integrating metal backshort