Superconducting Transition Edge Sensors (TES)

By:

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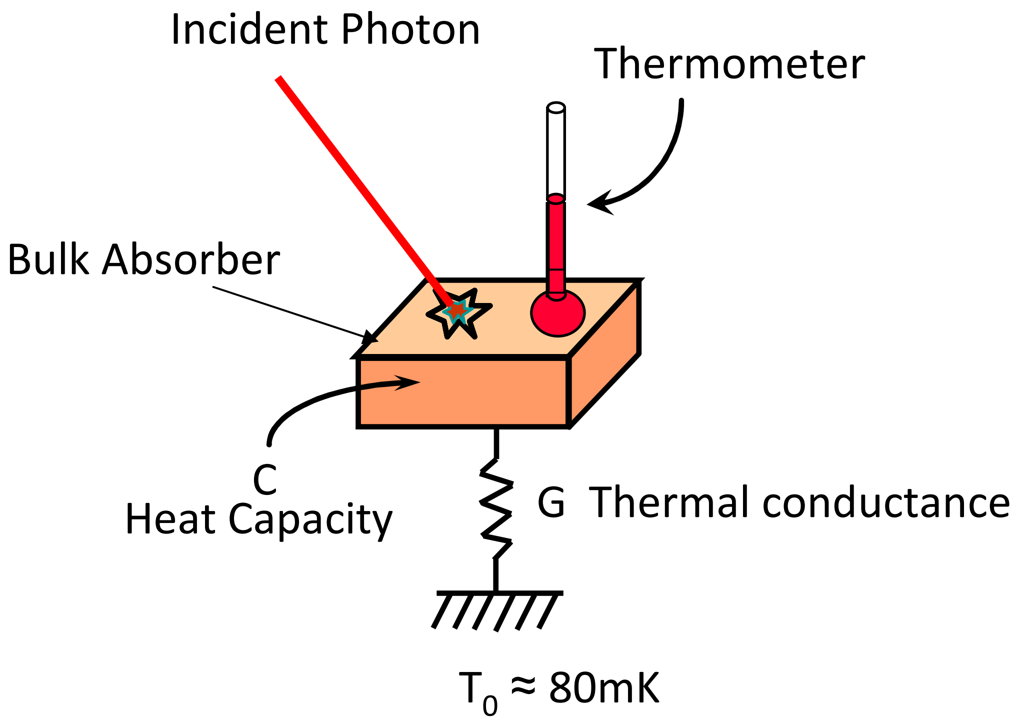
Outline

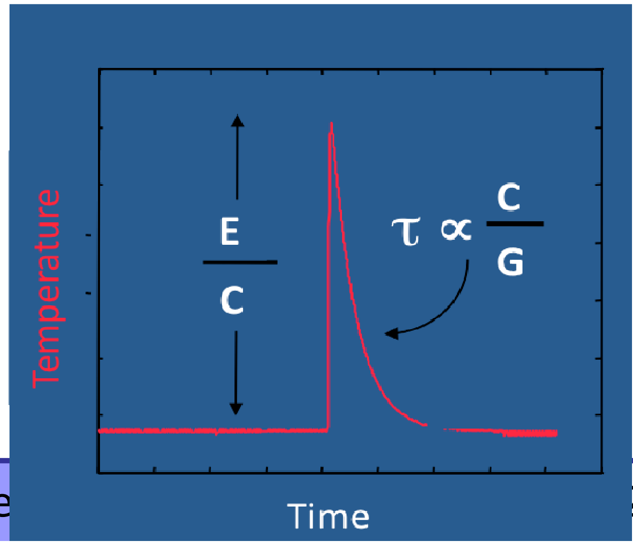
- Introduction
- Applications:
  - Detectors for Astronomy
  - Microcalorimeters for Gamma-ray Spectroscopy
- Optics Alignment Tool
- Conclusions

- Thermometer and absorber are connected by a weak thermal link to a heat sink.

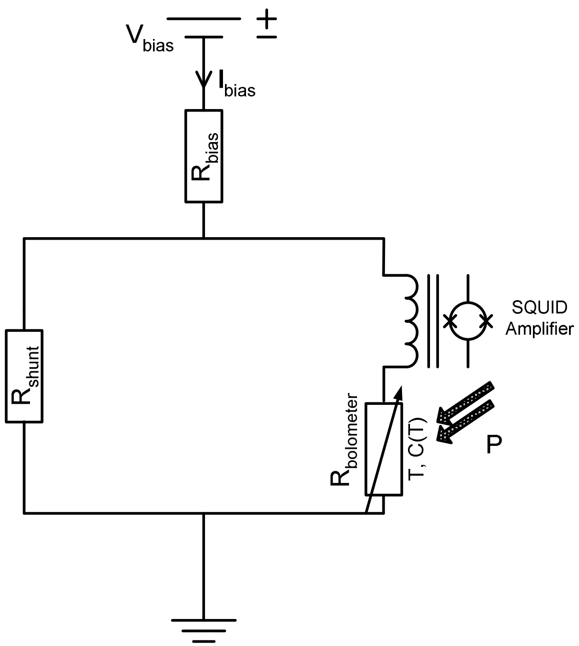
- Incoming energy is converted to heat in the absorber: $\Delta T = T - T_0 = E/C$.

- Temperature rise decays as power in absorber flows out to the heat sink $\tau = C/G$.





Voltage biased circuit: TES:



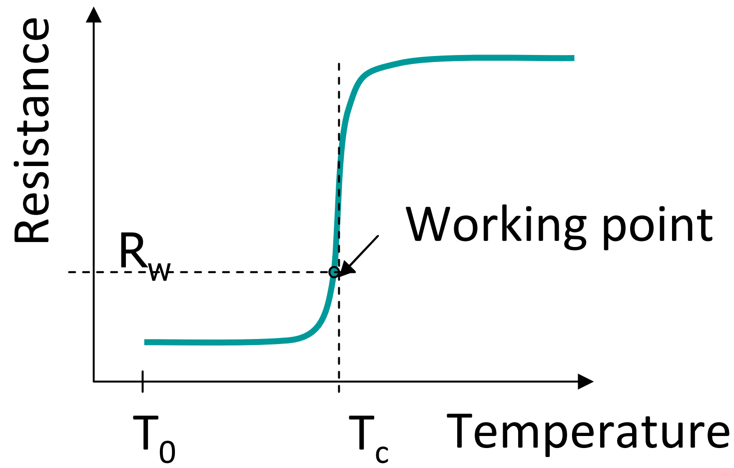
- The strong negative ETF maintains the transition temperature.
- Sharp transition speeds up the detector so lower time constant.
- Higher sensitivity.
- SQUIDs and multiplexing of SQUID electronics.

Strong Negative Electrothermal Feedback

1) $P_{Total} = P_{Signal} + P_{Bias}$ where $P_{Bias} = V_0^2/R$

$T \uparrow \Rightarrow R \uparrow \Rightarrow P_{Bias} \downarrow \Rightarrow P_{Total} \downarrow \Rightarrow T \downarrow$

2) Faster bolometer response $\tau_0 = \dfrac{C}{G}$ $\tau = \dfrac{\tau_0}{L+1}$



Detectors:

Thin film thermometers.

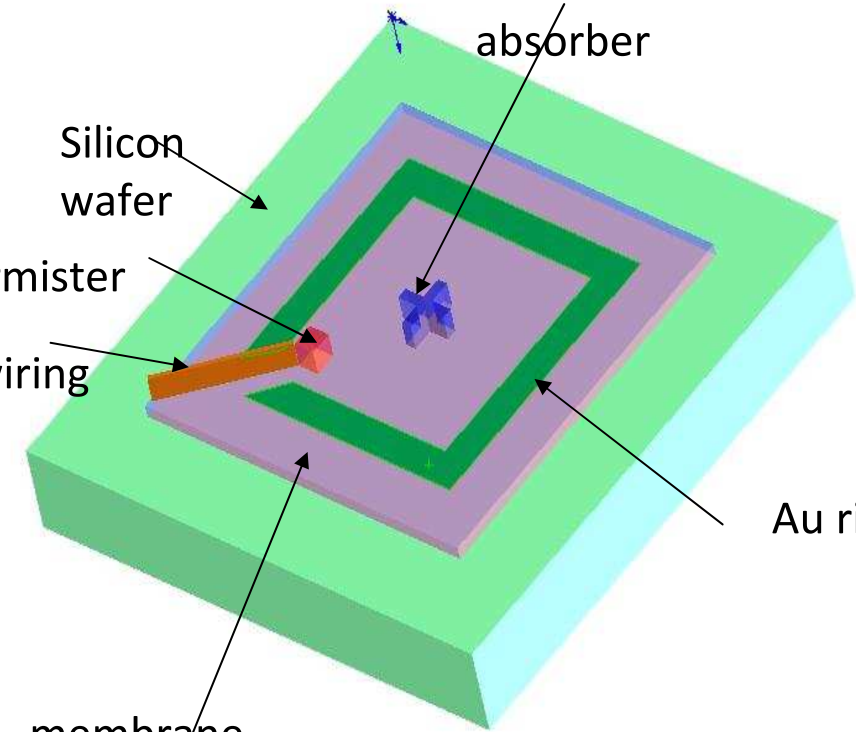
Bi-layer thermometers.

MPIfR→ Gold-Palladium (8 nm)/Molybdenum (60 nm)→450±25mK

NIST→ Copper (0.1μm)/ Molybdenum (0.2μm)→120 ±10mK

Application: Astronomical detectors

- Au-Pd / Mo bilayer structure thermistor
- Transition temperature $T_c \approx 450$ mK
- Thermistor is mounted on silicon nitride (Si_3N_4) membrane.



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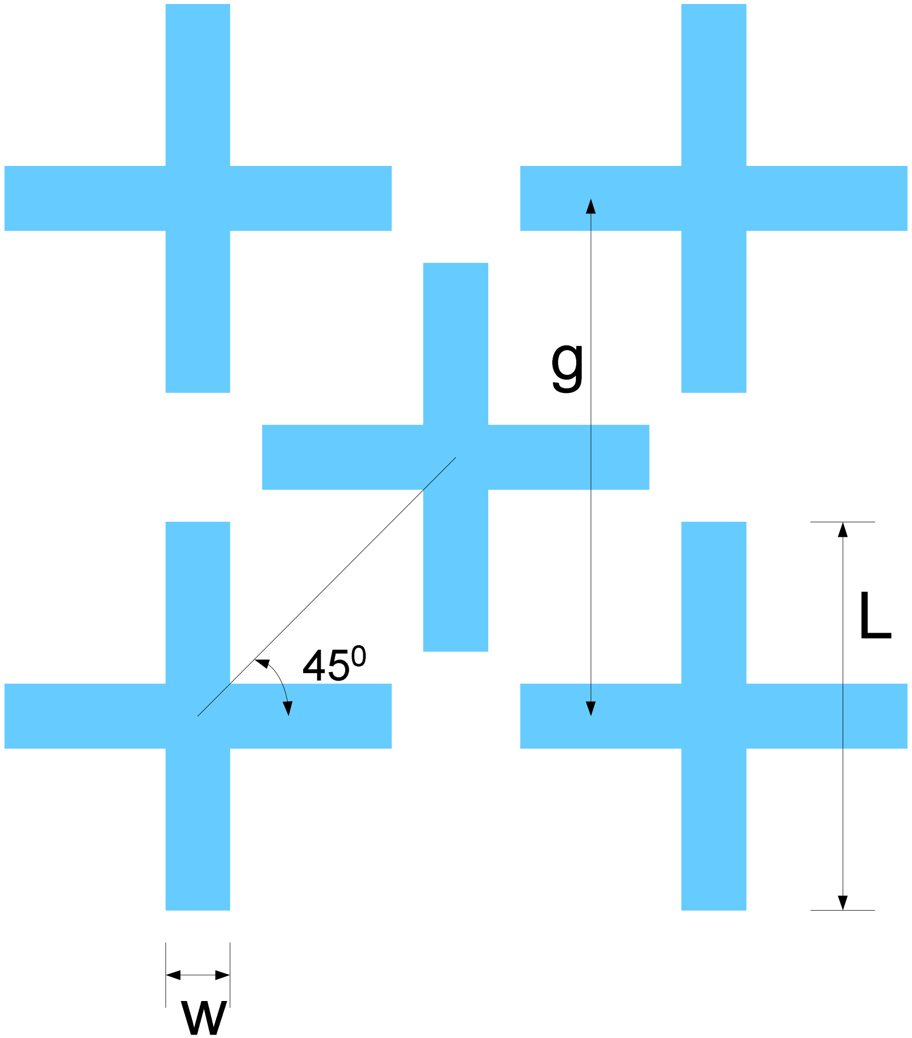
Au–Pd cross absorber

- Gold-palladium alloy
- Surface resistance = 10 $\Omega/\square$

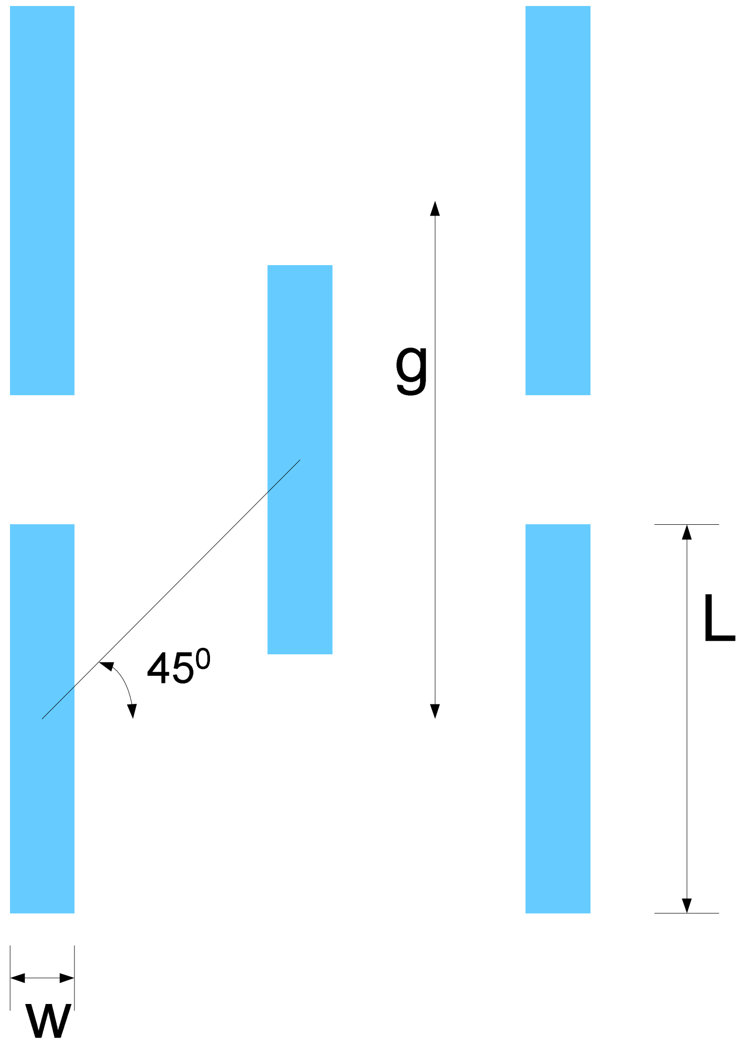
$$A = \left|\frac{4n}{(1+n)^2}\right| \frac{4Z_0 nR}{\left|R(1+n)+Z_o\right|^2}$$



Au–Pd cross absorber

- Gold-palladium alloy
- Surface resistance = 10 $\Omega/\square$

Polarization sensitive absorbers

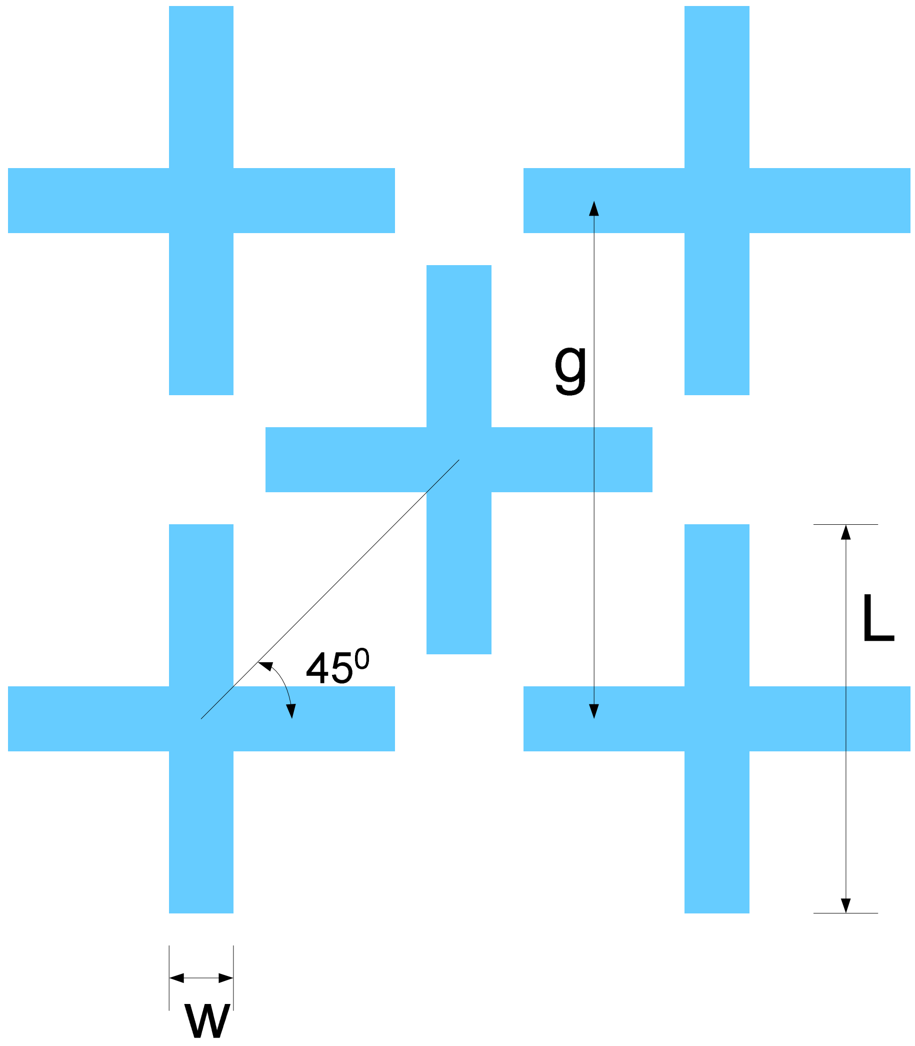


Au–Pd cross absorber

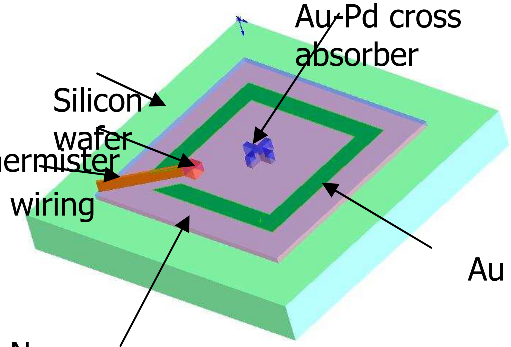
- Gold-palladium alloy
- Surface resistance = 10 Ω/□

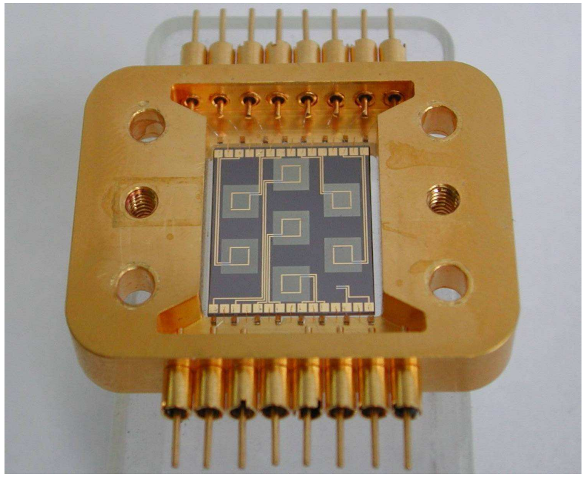
Advantages:

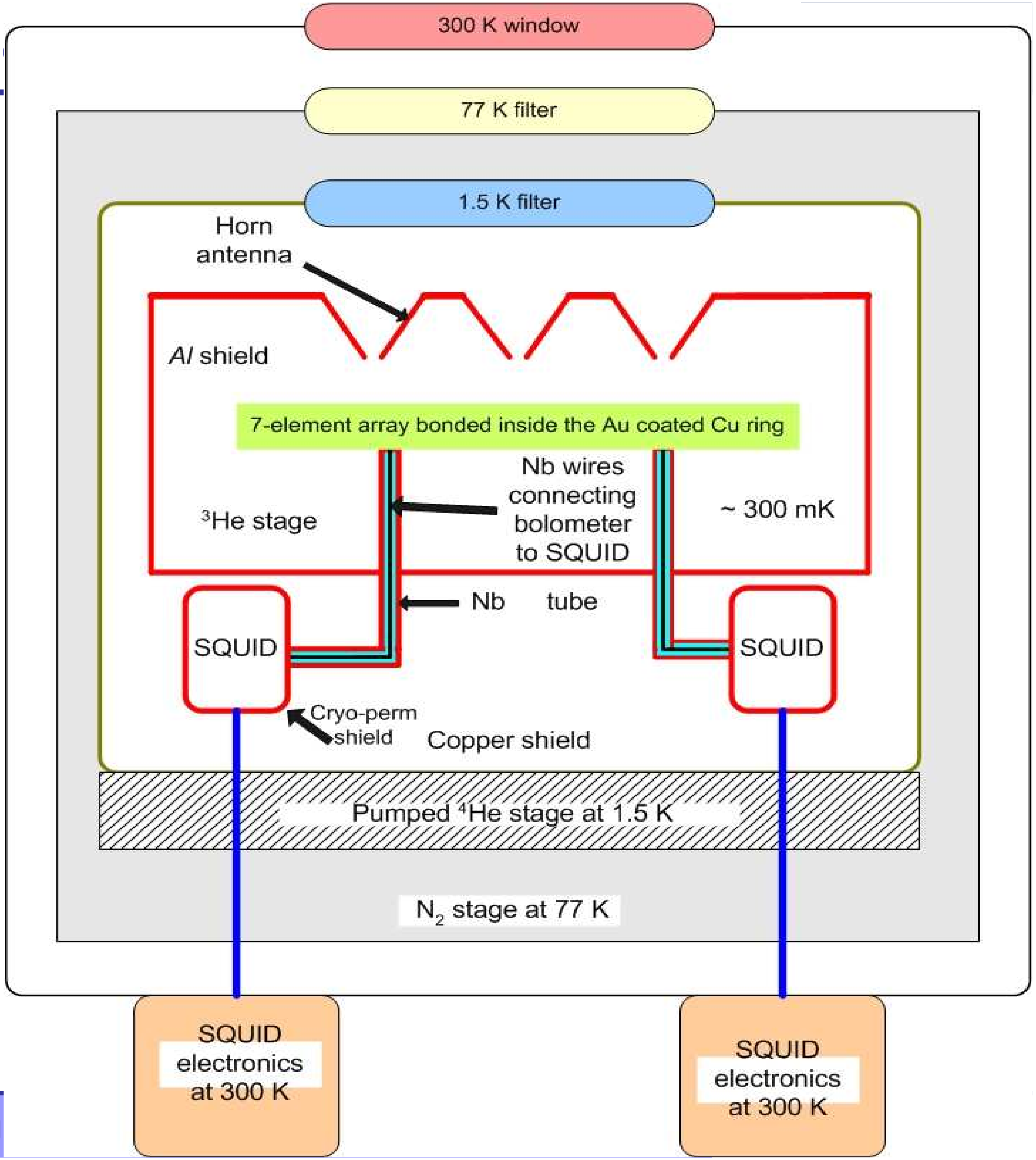
- Frequency selective absorber, L=λ/2
- Polarization sensitive absorber

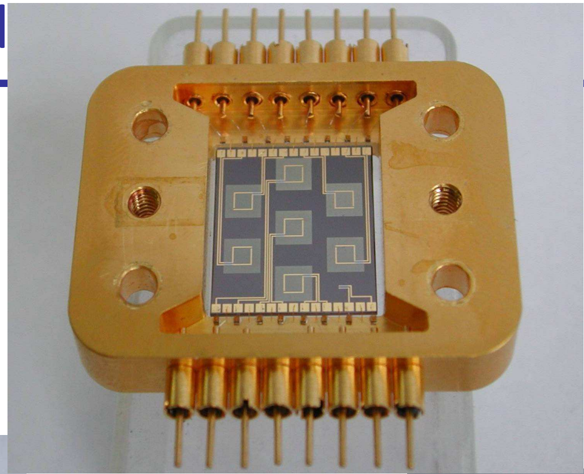


Application: Astronomi

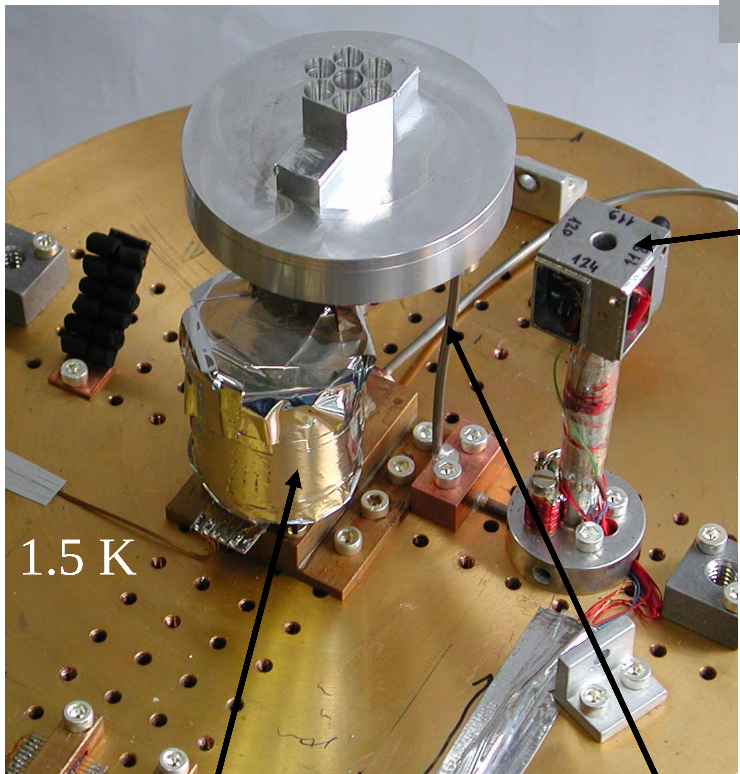






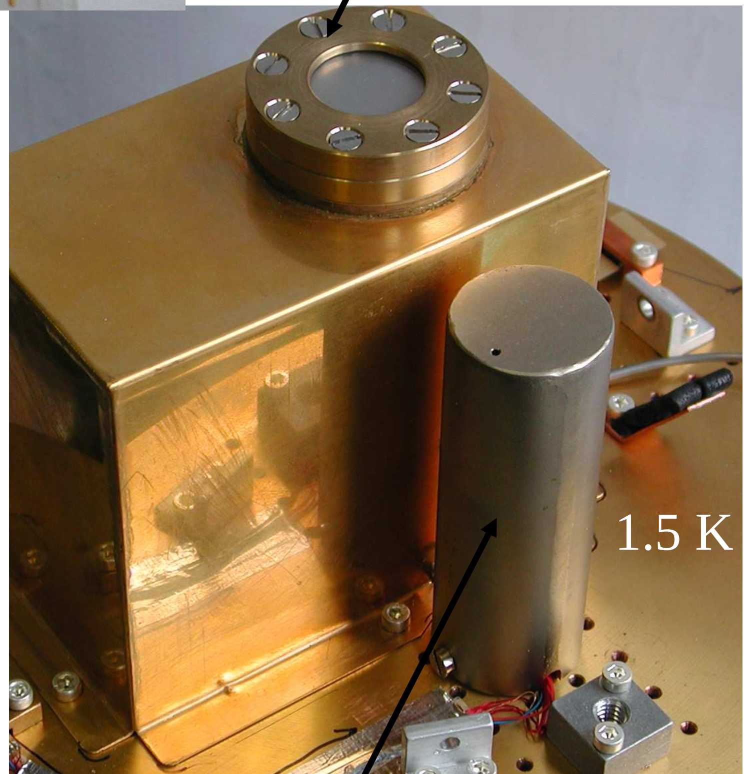


Superconducting aluminium
Hornarray/cavity at 0.3 K



4 SQUIDs
at 1.5 K

1.5 K filter



Sorption pump

Niobium tube

Cryo-perm shield

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TES equations:

$$S_i \equiv \frac{\delta I}{\delta P} = -\frac{1}{V_{BIAS}} \cdot \frac{L}{(L+1)} \cdot \frac{1}{(1+i\omega\tau)}$$ current response

$$L(\omega) = \frac{P_{BIAS} \cdot \alpha}{GT(1+i\omega\tau_0)}$$ AC open loop gain

1) Structuring of Si_3N_4 membrane.

2) Estimation of G.

Finite Element Analysis

(WWW.COSMOSM.COM)

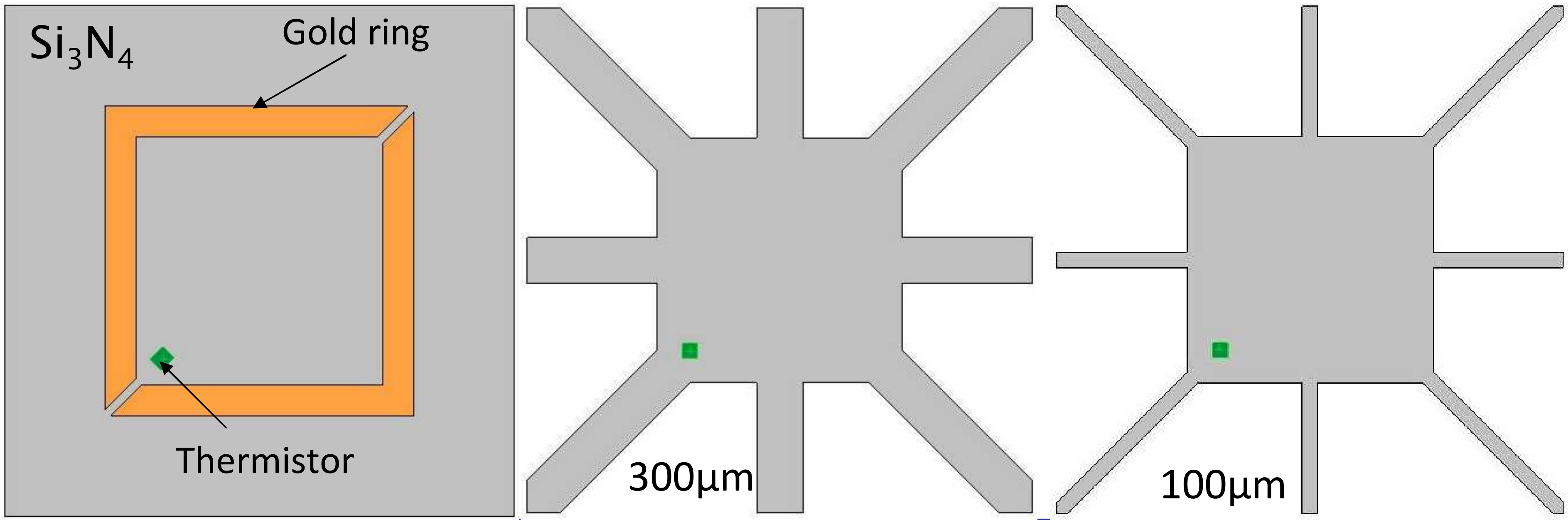
Application: Astronomical detectors

Silicon nitride membrane

- The thermal conductance is tuned by structuring the silicon nitride membrane.

$$\text{sensitivity} \propto \frac{1}{\text{thermal conductance}}$$

High-G | Medium-G | Low-G

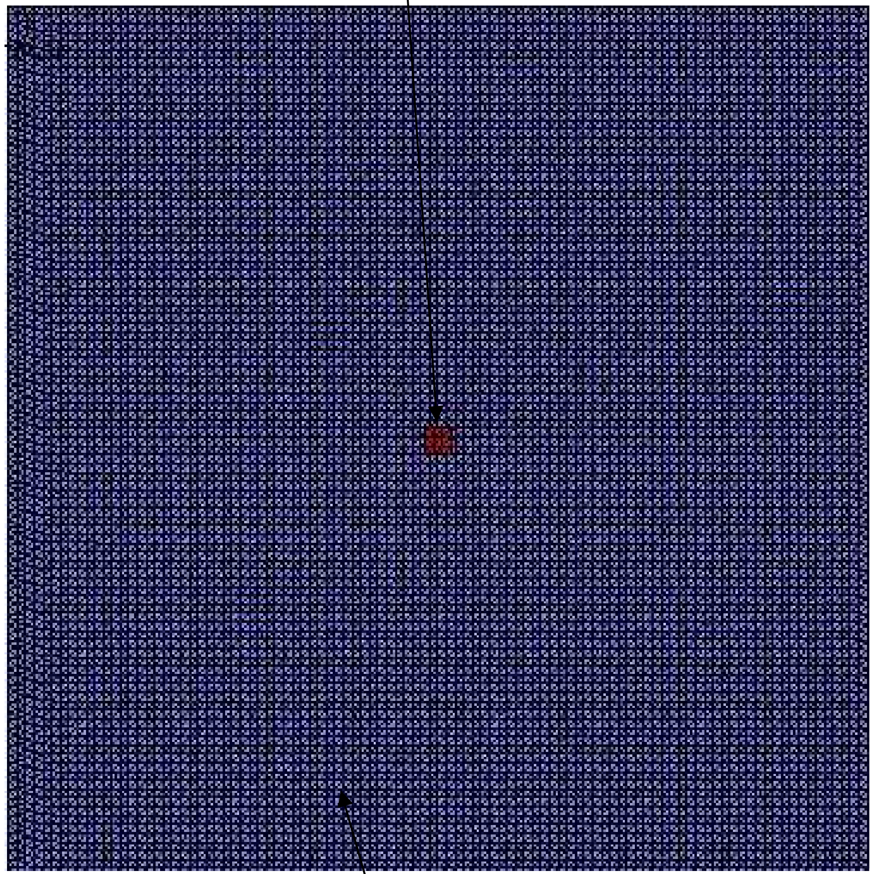


Thermal modeling

- Thermal analysis using COSMOS

$$G_{so} = k\left(A/L\right)$$

- Thermal conductivity (*k*) values are obtained from Holmes et al.
  Applied Physics letters 72, 18, 1998

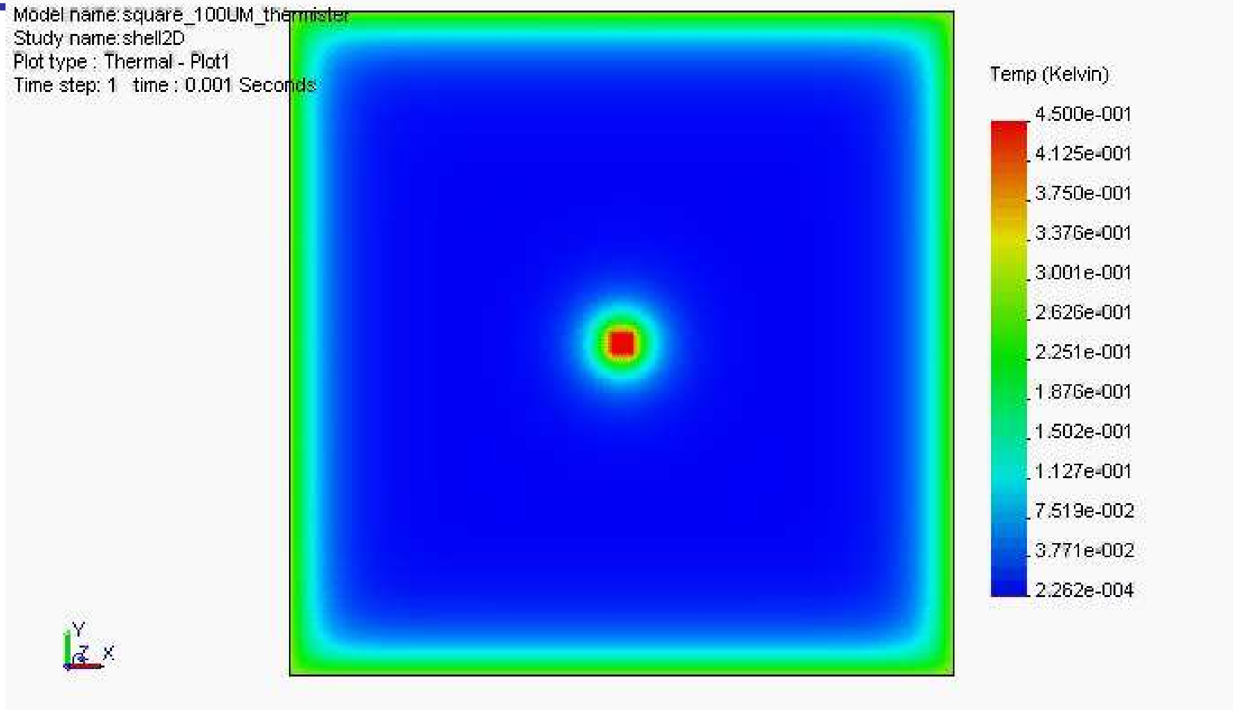


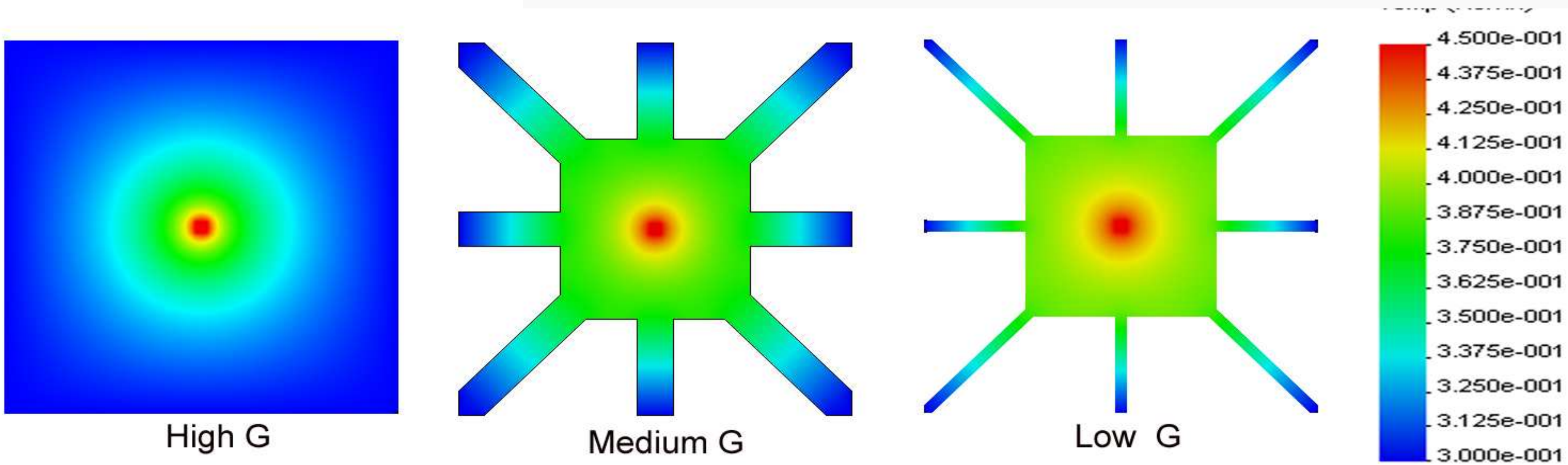
Application: Astronomical detectors

Thermal modeling

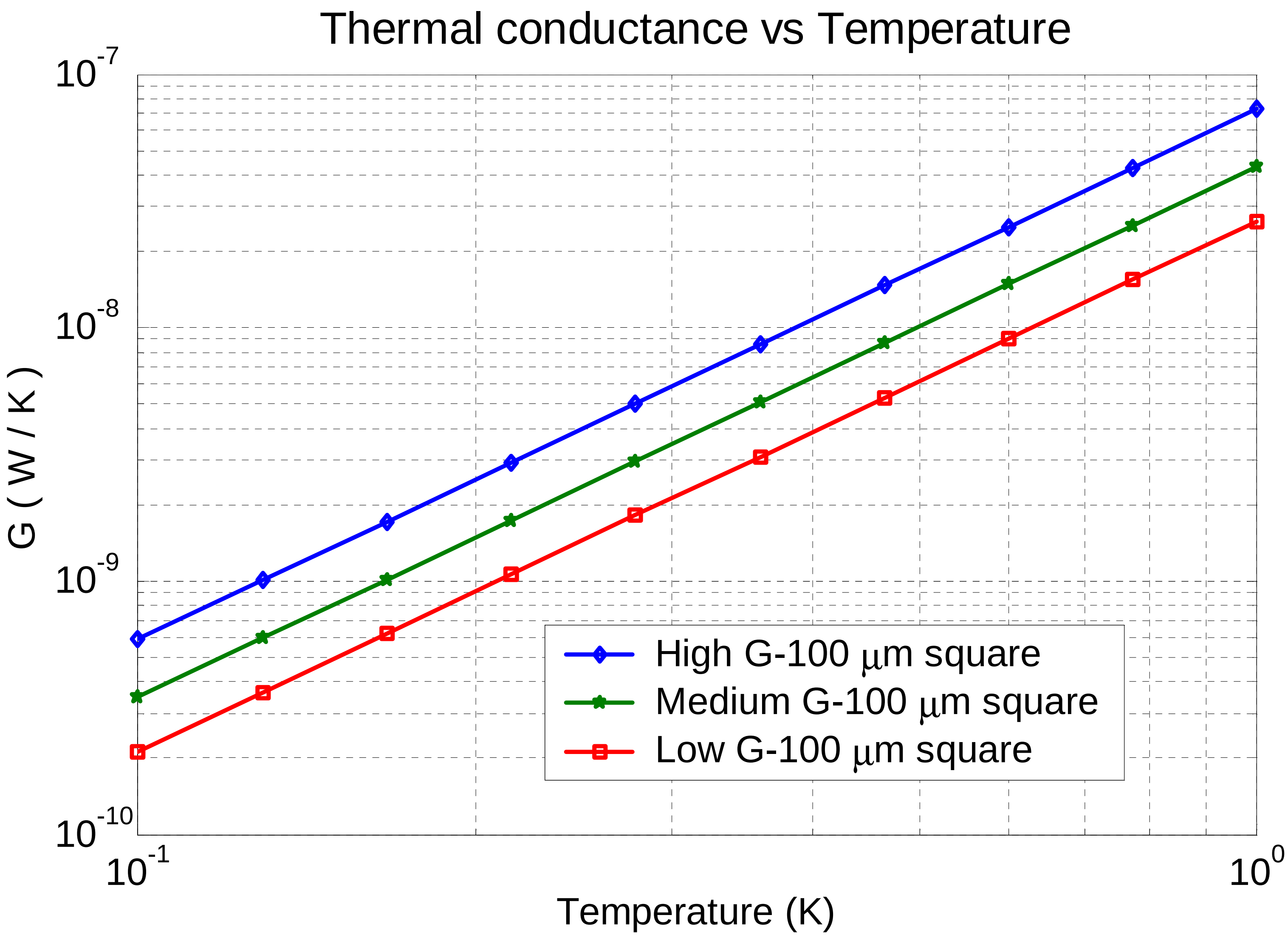
-COSMOS

Bolometer response
to the periodic signal.

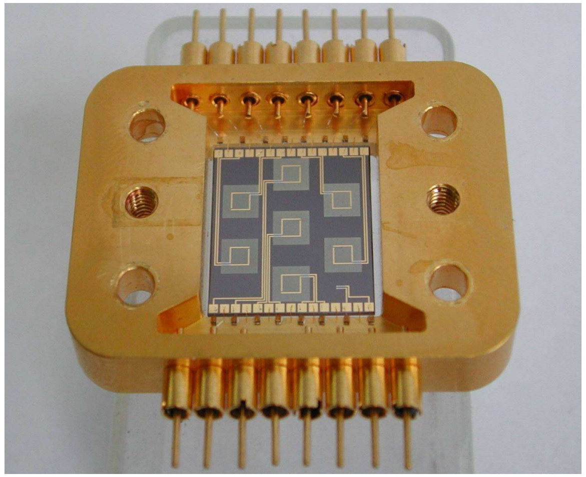




Thermal conductance



Application: Astronomical detectors



7-element array

39-element array

Small Bolometer
CAmera (SABOCA)

Application: Astronomical detectors

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APEX

The Atacama Pathfinder Experiment

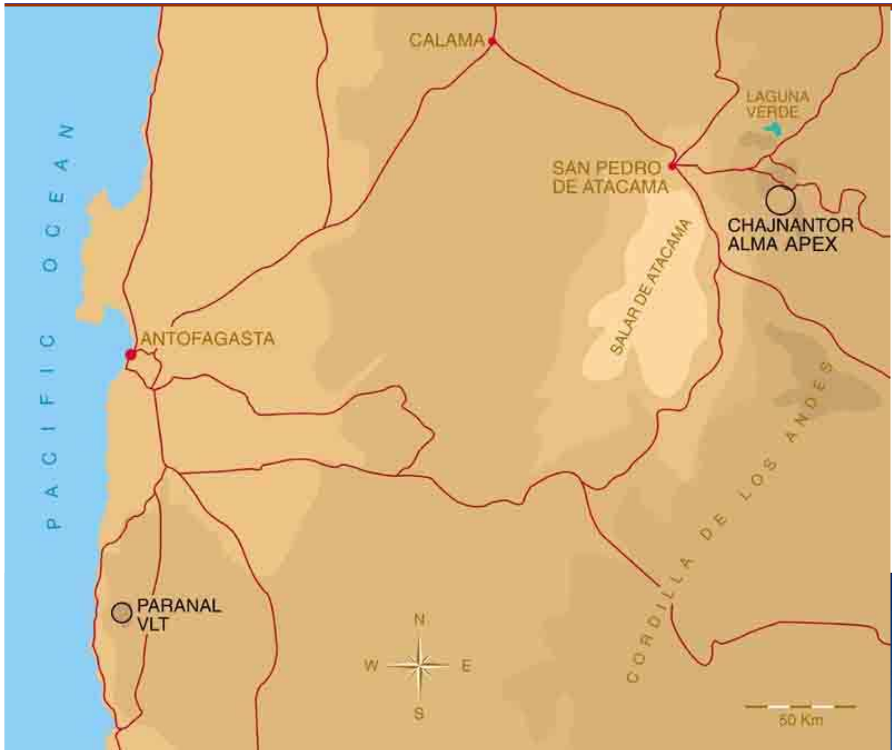
Max-Planck-Institut
für
Radioastronomie

ESO

ONSALA RYMDOBSERVATORIUM
CHALMERS TEKNISKA HÖGSKOLA

12m - Submillimeter telescope APEX

Application: Astronomical detectors



Chajnantor Plateau

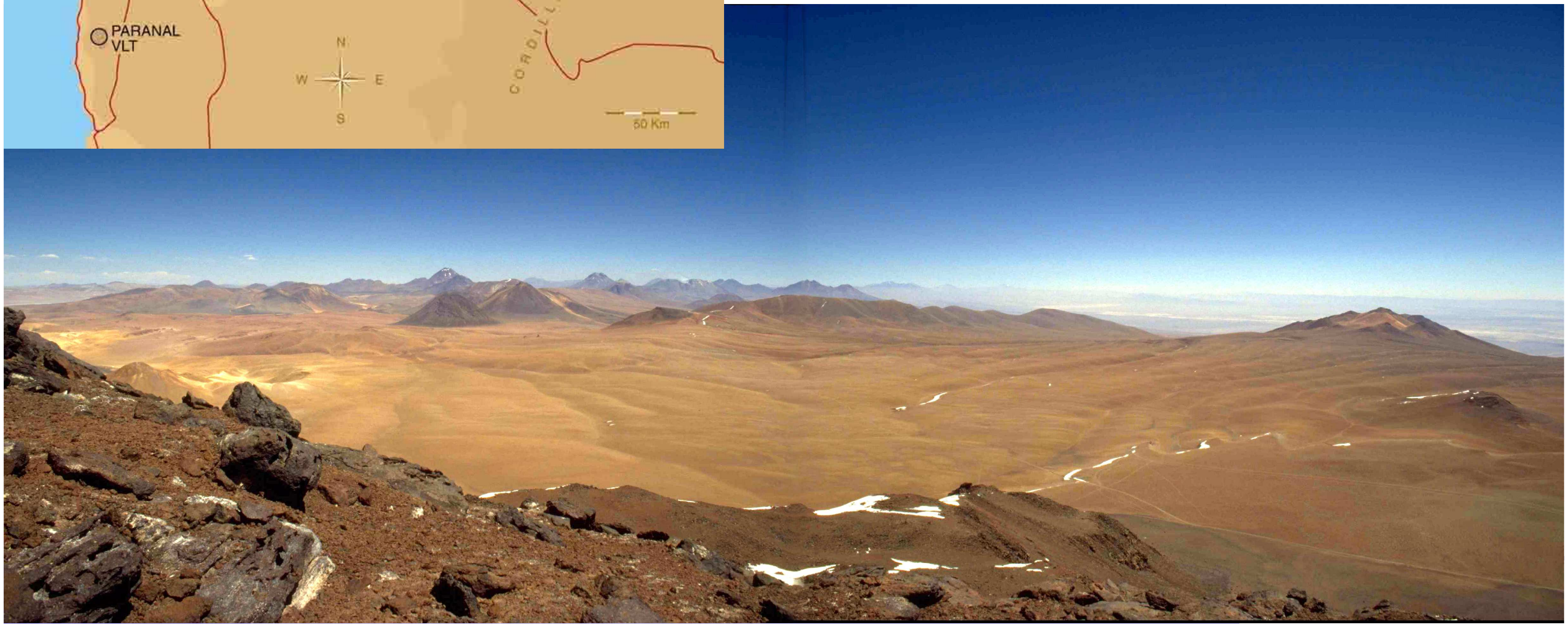
Atacama, Chile

Latitude 23 deg south

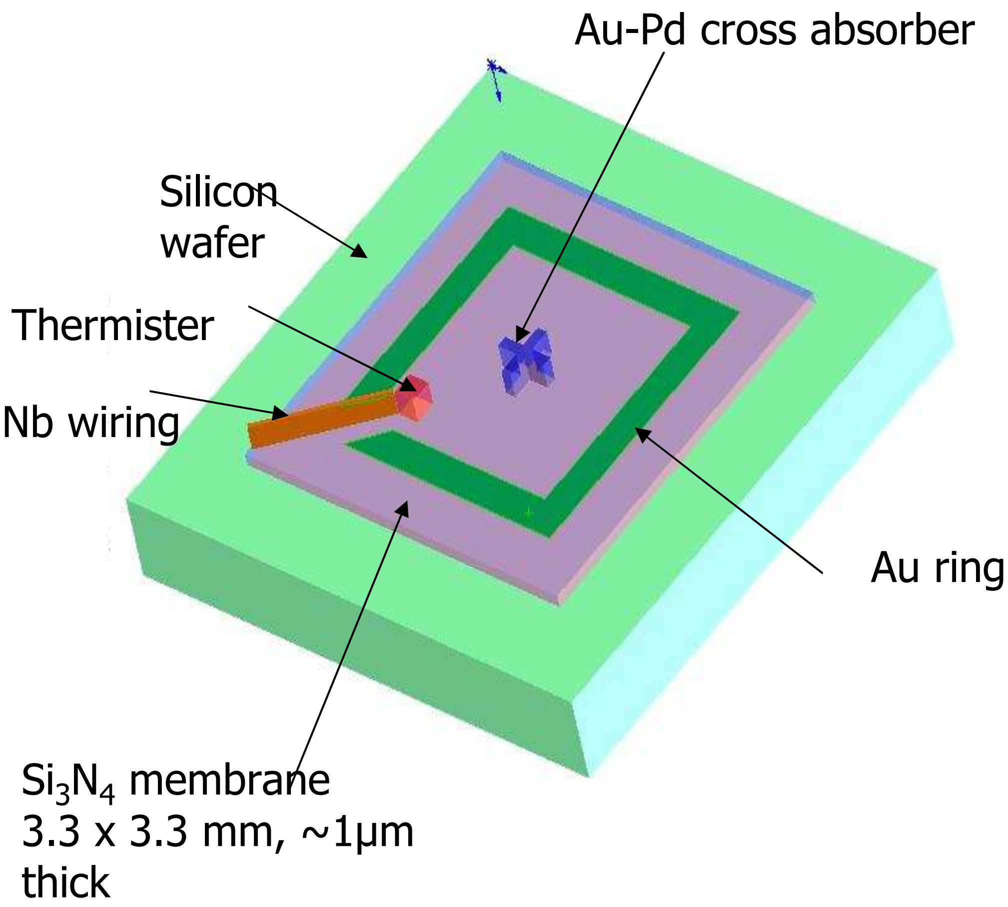
Longitude 68 deg west

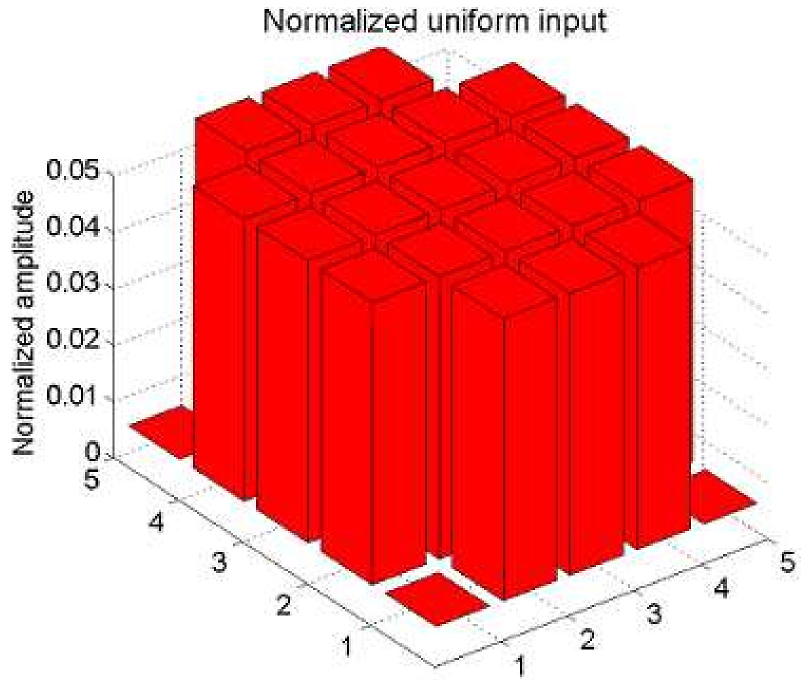
Altitude 5100 m=16700 feet

230 GHz → 1.5THz



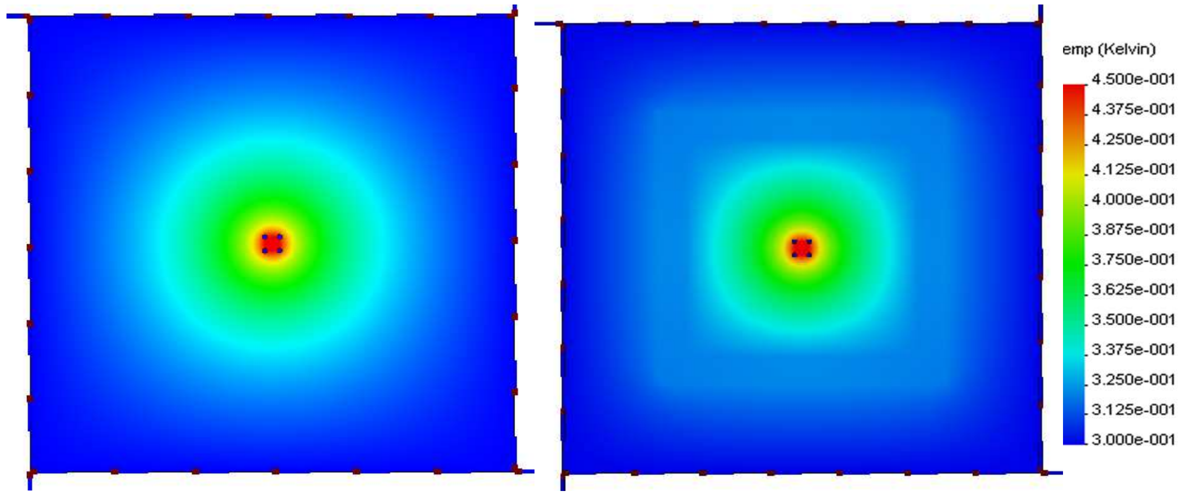
Application: THz scanner

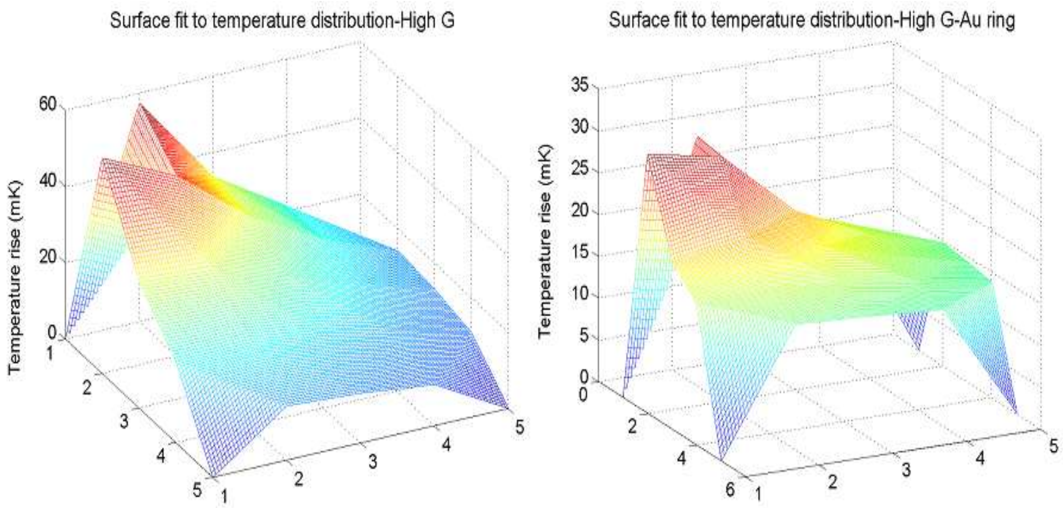




Application: THz scanner

Without center Au ring | With center Au ring

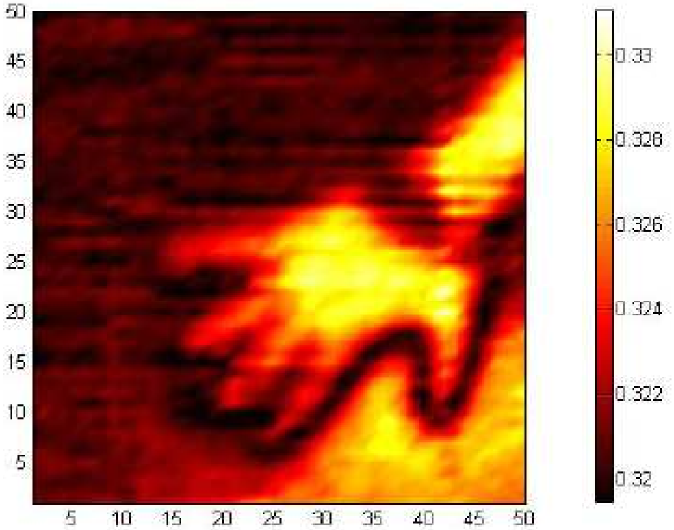




- FEA simulations showed increase
 in thermalization by depositing the center ring around radiation absorbing area.

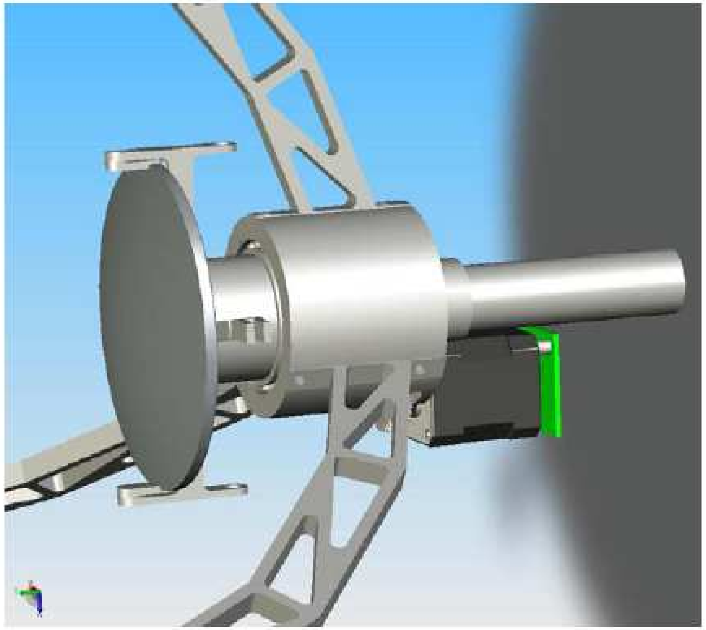
- Detectors successfully used for Terahertz application.

Application: THz scanner

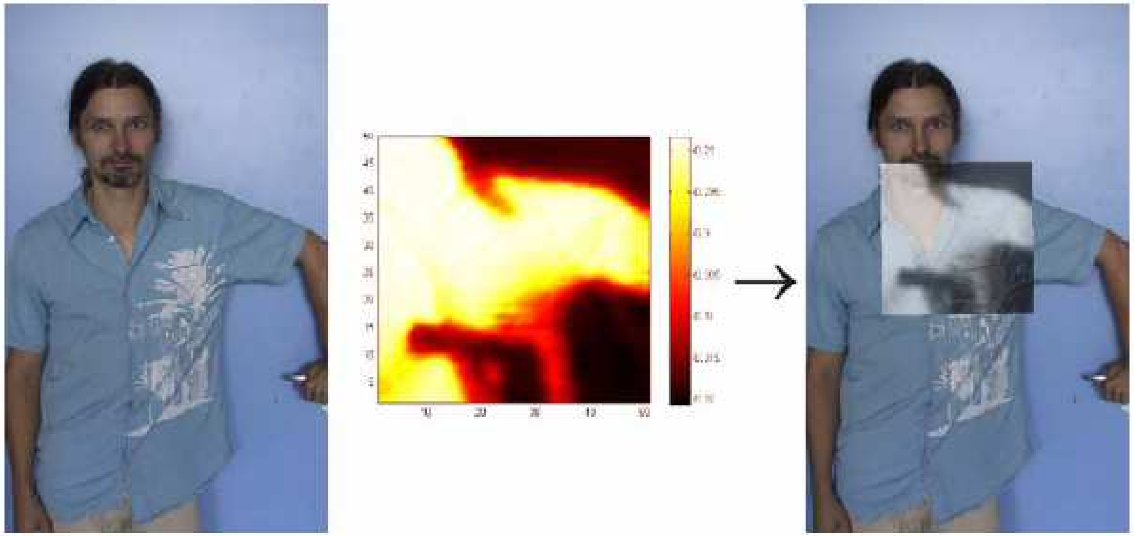


Human hand at 0.34 THz, from 5 meter distance

Design of an optical scanner based on a gyrating mirror

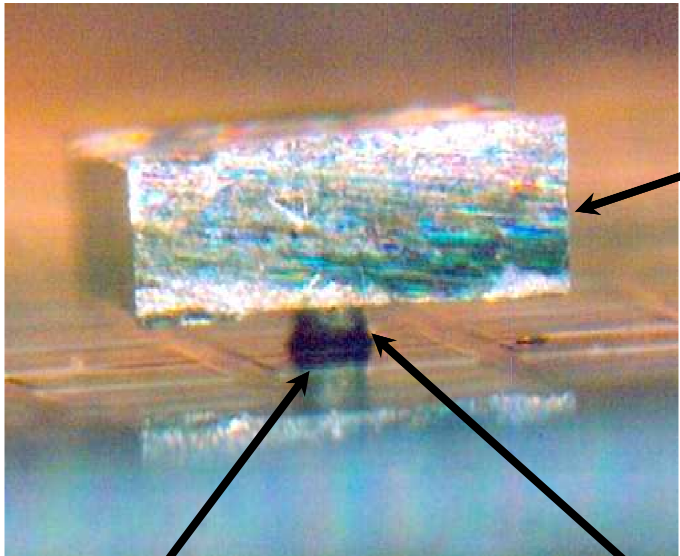


Test scenario: a test person hides a handgun mock-up underneath its shirt, and the THz scan reveals the threat from 5 meter distance.



Application: γ-ray spectroscopy

To stop gamma-rays, a bulk absorber is required



Microcalorimeters can provide
ΔE < 50 eV FWHM at 100 keV !

State-of-art germanium = 500 eV

	µcal	Ge	
ΔE	50 eV	500 eV	
area	1-2 mm^2	~500 mm^2	
Γ	~100 Hz	~50 kHz	
QE	25% (at 100 keV)	~95%	

Application: γ-ray spectroscopy

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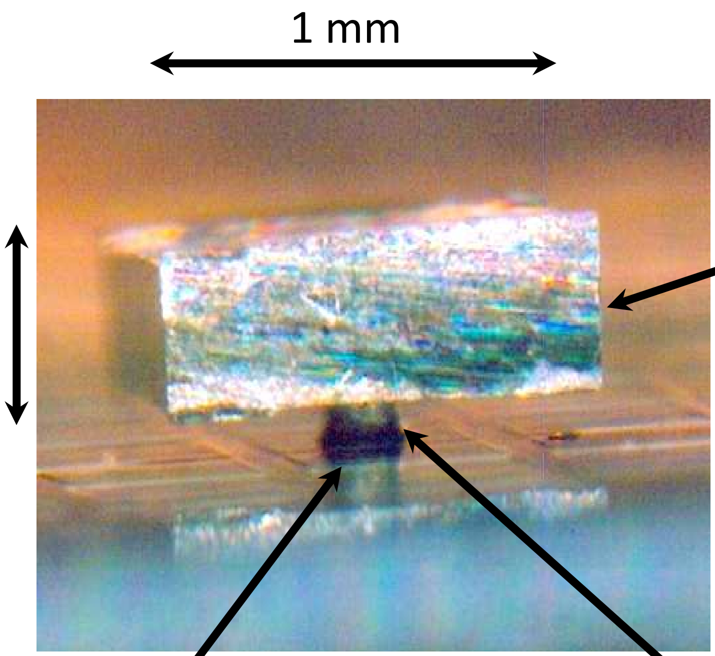


Microcalorimeters can provide
ΔE < 50 eV FWHM at 100 keV !

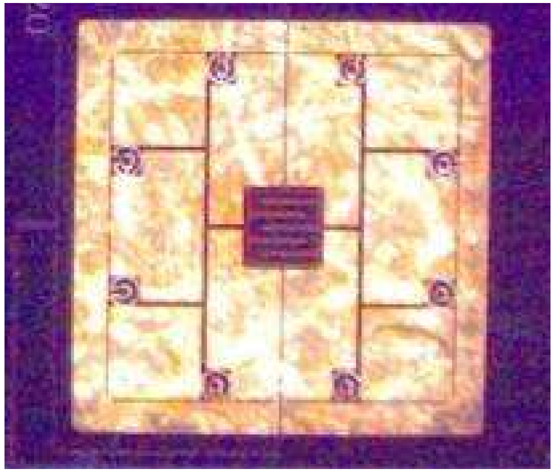
State-of-art germanium = 500 eV

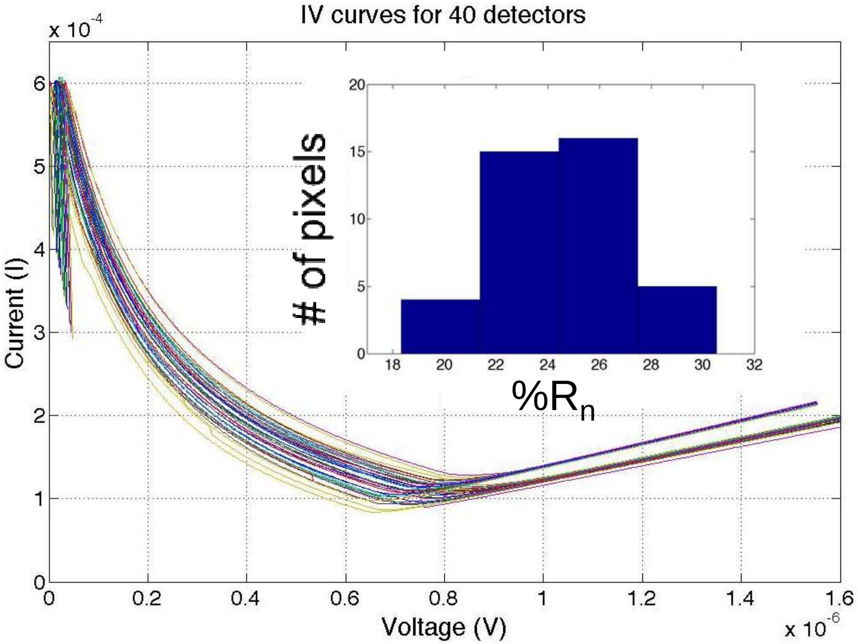
	μcal	Ge	256 ucal
ΔE	50 eV	500 eV	50 eV
area	1-2 mm^2	~500 mm^2	~500 mm^2
Γ	~100 Hz	~50 kHz	~25 kHz
QE	25% (at 100 keV)	~95%	25%

Microcalorimeter arrays may perform better than Ge for some apps – Pu isotopics

Microcalorimeter arrays may enable new applications – Pu in spent reactor fuel

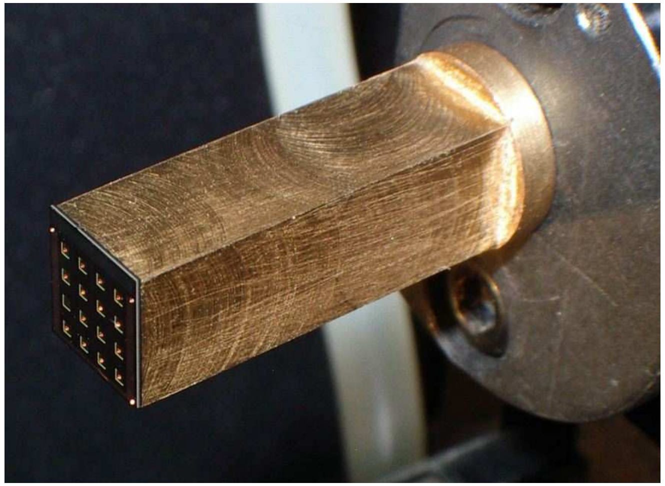
Application: γ-ray spectroscopy

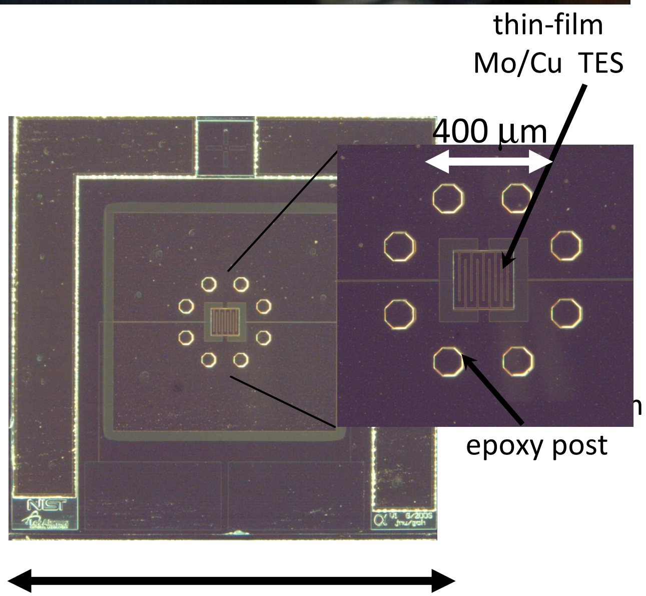


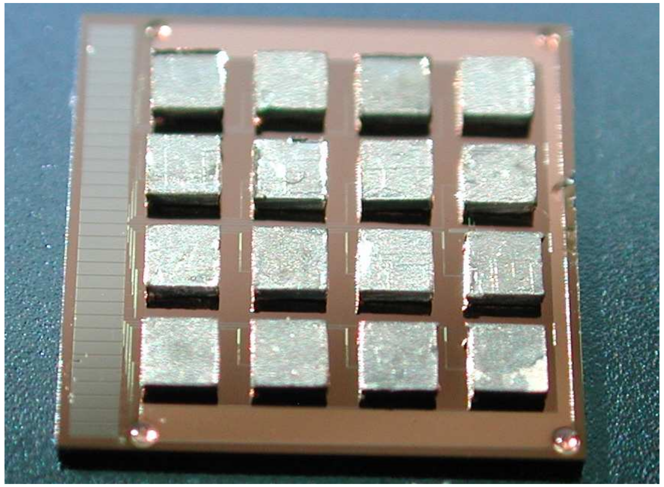


- multi-post design
  - better mechanical support for the absorber
  - reduced mechanical and chemical stress on the TES thermometer
  - reduced dependence of pulse height on interaction position
- larger absorber area for higher detection efficiency (2.25 mm^2 vs. 1 mm^2)
- larger dynamic range, better linearity

Application: γ-ray spectroscopy

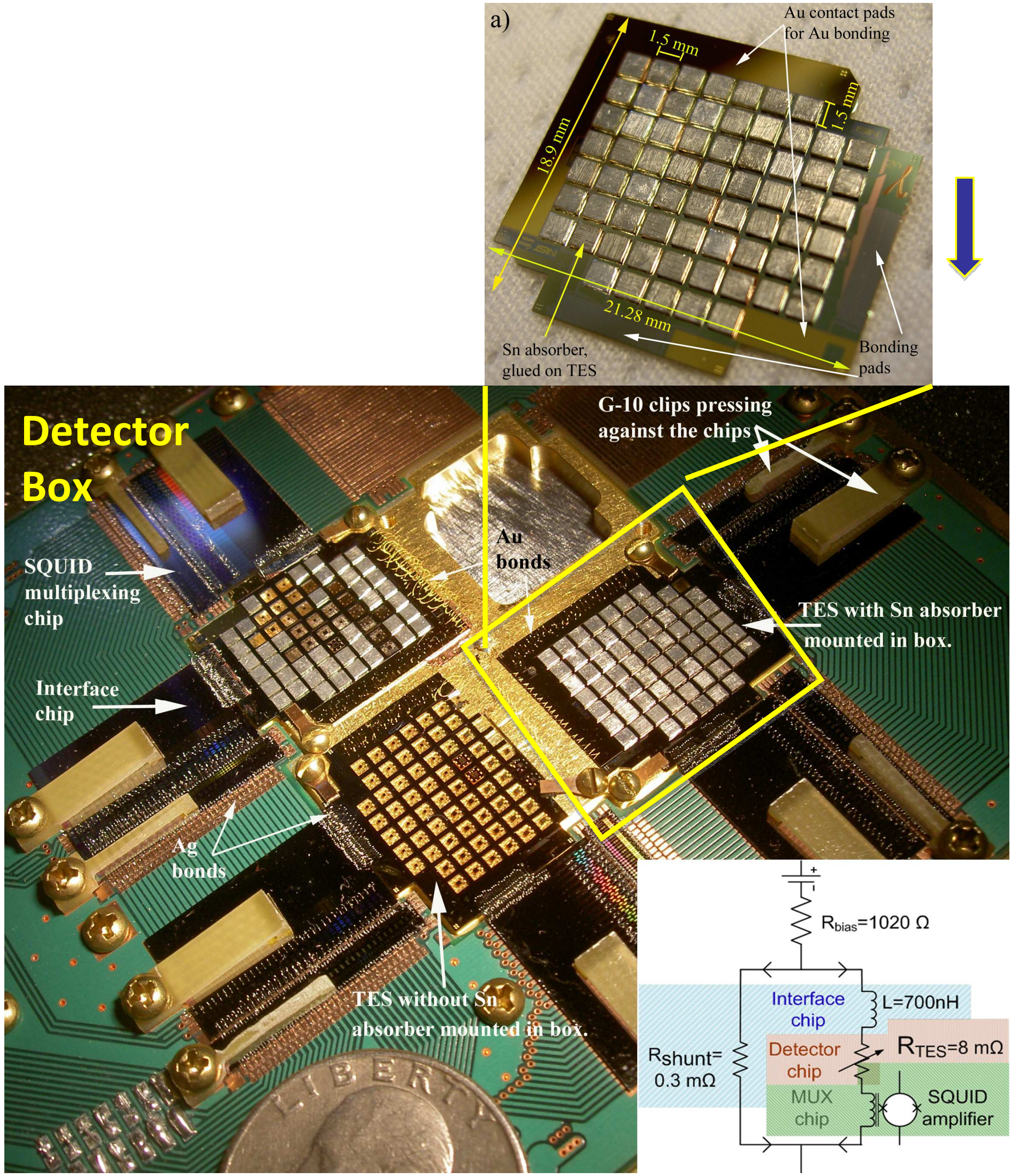






Gamma-ray detectors

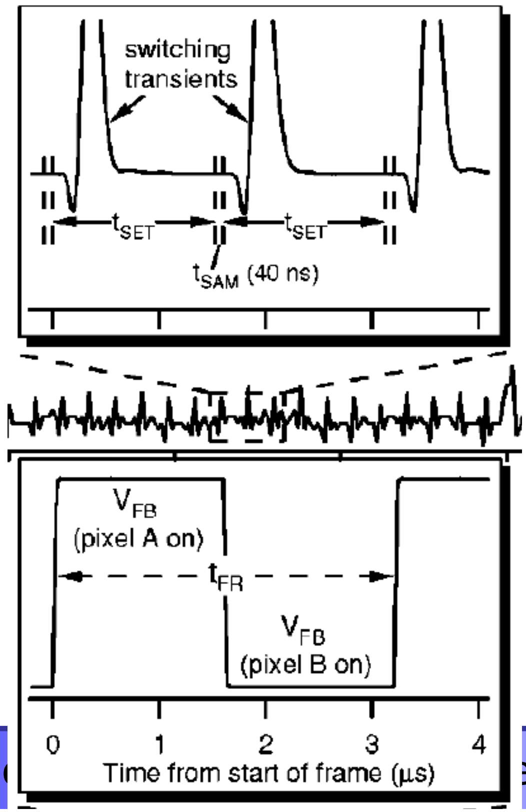
- 55 working detectors out of total 66 detectors.
- 31 Multiplexing detectors.
- Linear from 60 KeV – 130 KeV region.

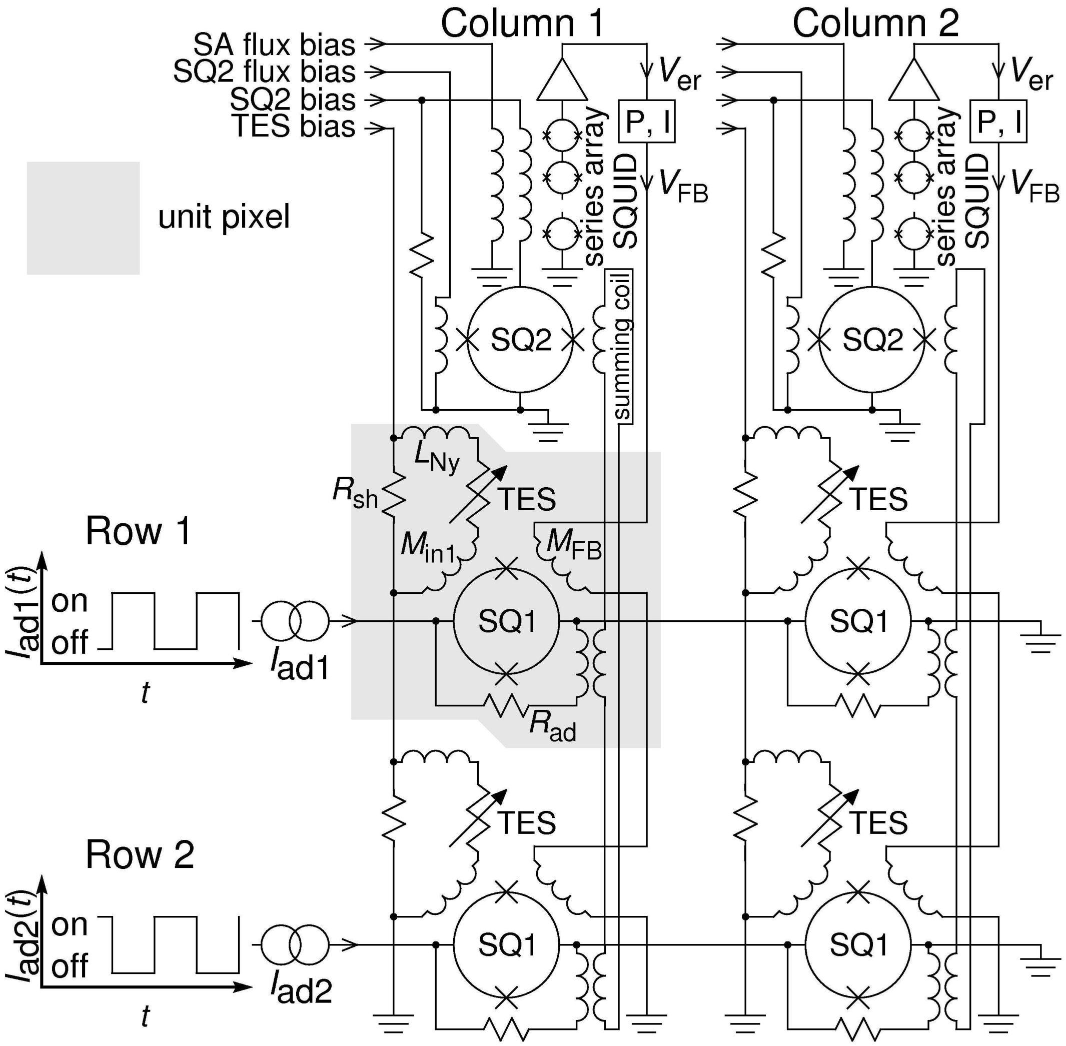


Time division multiplexing: SQUIDs

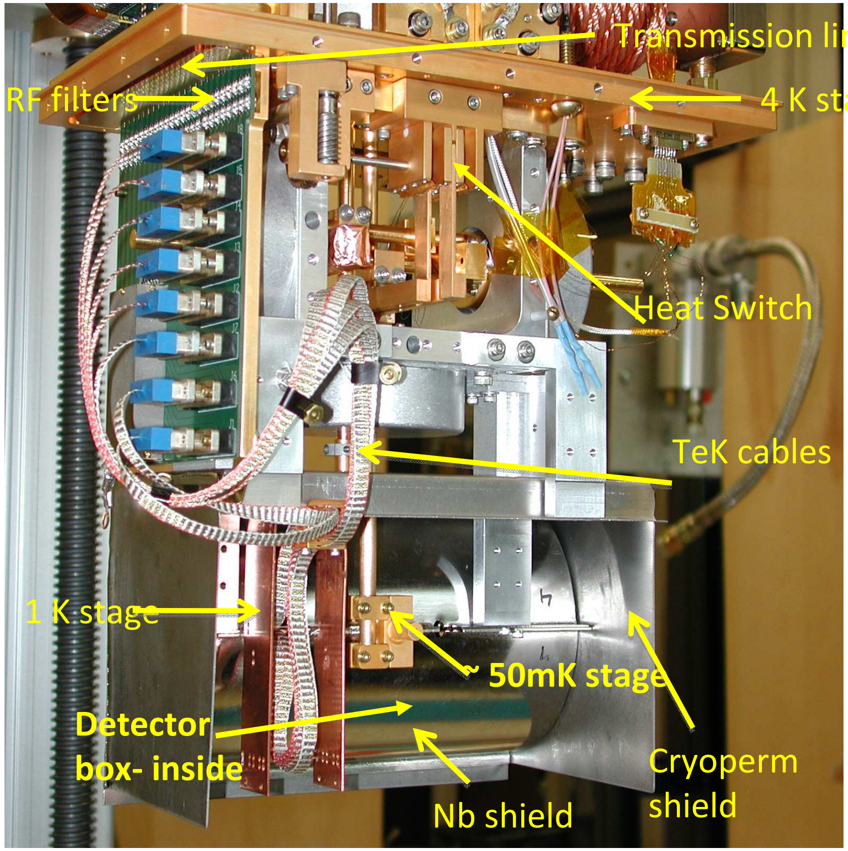
- Three stage SQUID wiring.
- Flux-locked loop.

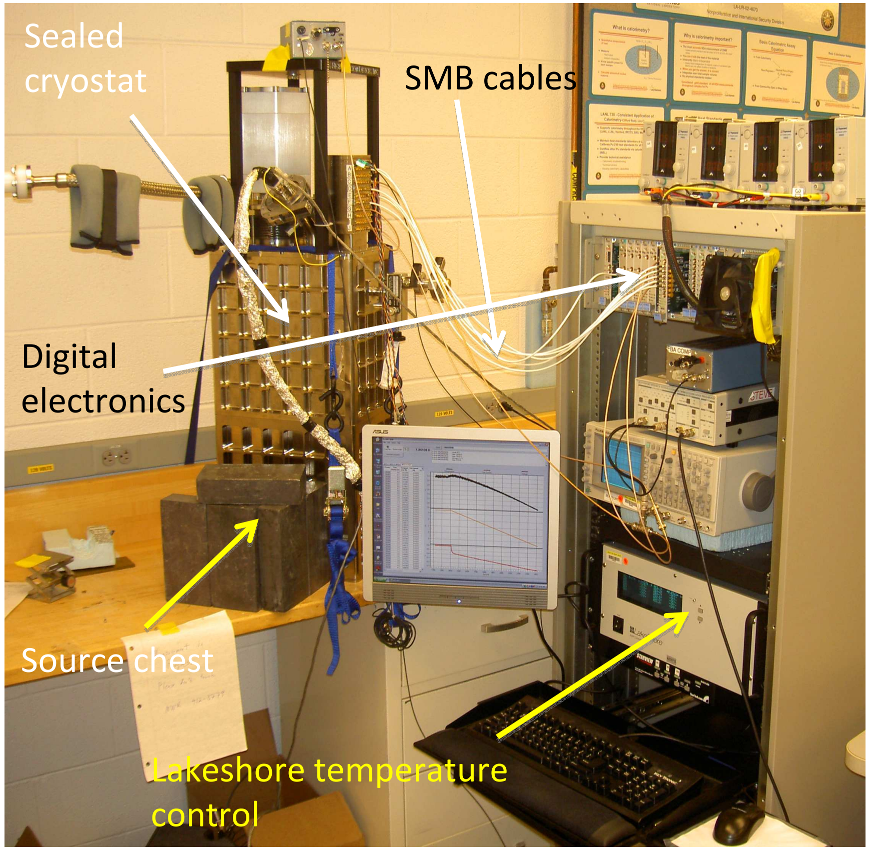
$$t_{FR} = N_{MUX}(t_{SET} + t_{SAM})$$





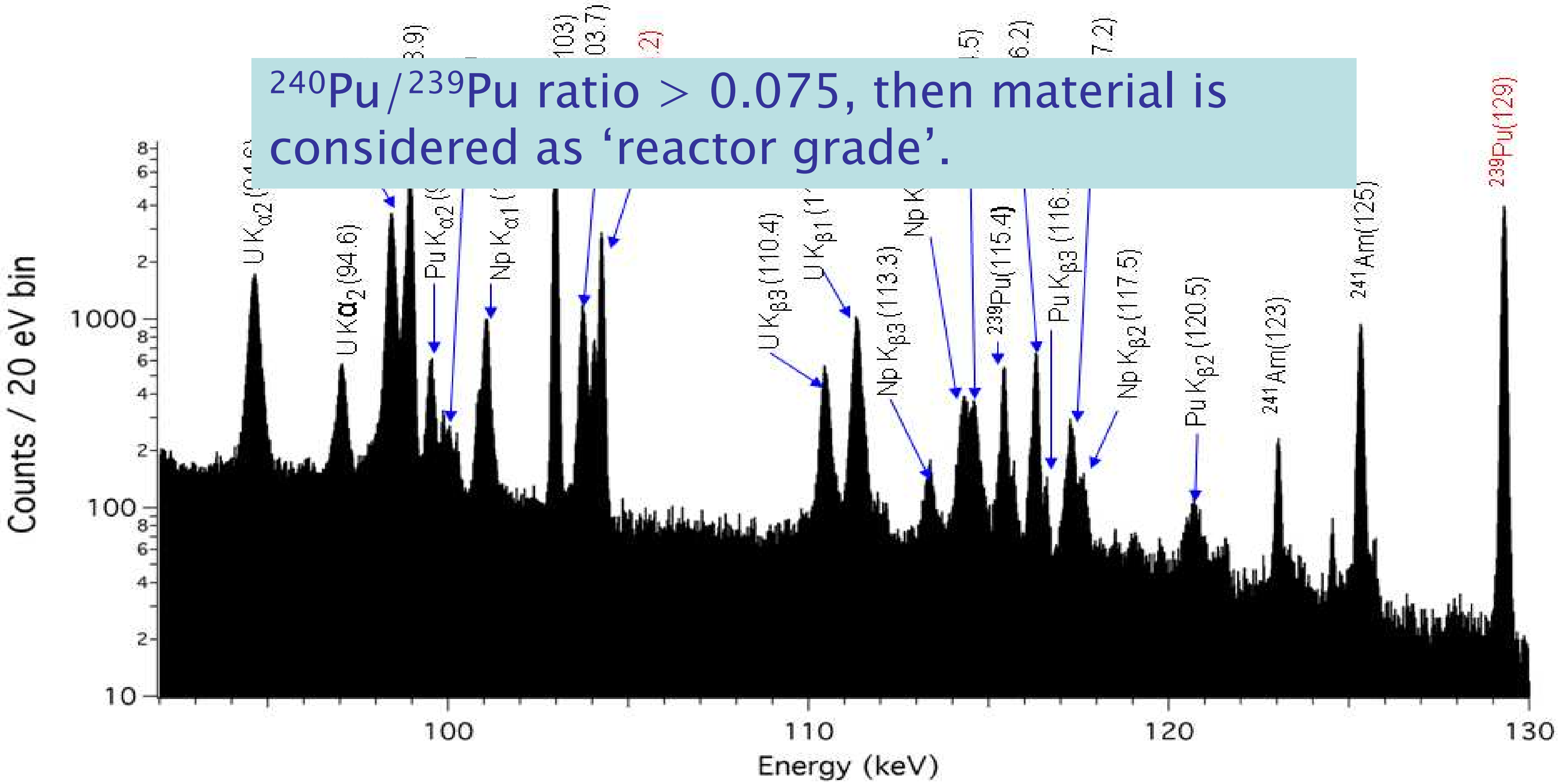
Gamma-ray cryogenics





- Configuration allowing 264 detectors.
- Typical base temperature=62mK, Temperature regulated at 100mK for 20 hours.
- No liquid cryogens; units working continuously at Los Alamos and NIST labs.

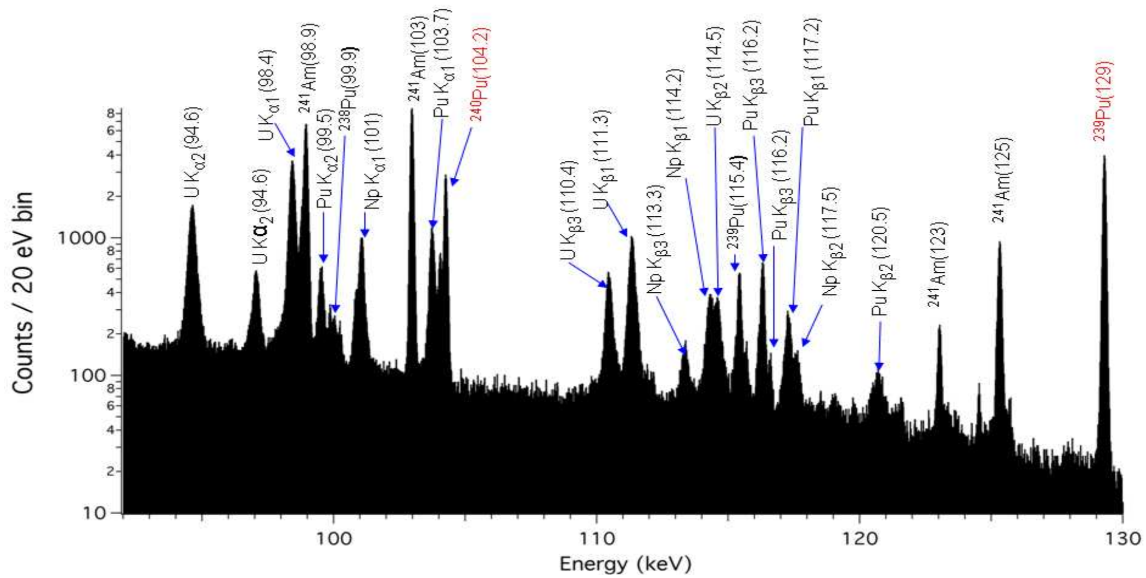
Plutonium Spectrum:



$^{240}Pu/^{239}Pu$ ratio > 0.075, then material is considered as 'reactor grade'.

1) Total: 38.9 million pulses. 2) ~18,700 ^{240}Pu counts→ for the first time using TES detectors. 3) ΔE ~ 120 eV. Expected resolution: 70 eV

Plutonium Spectrum:



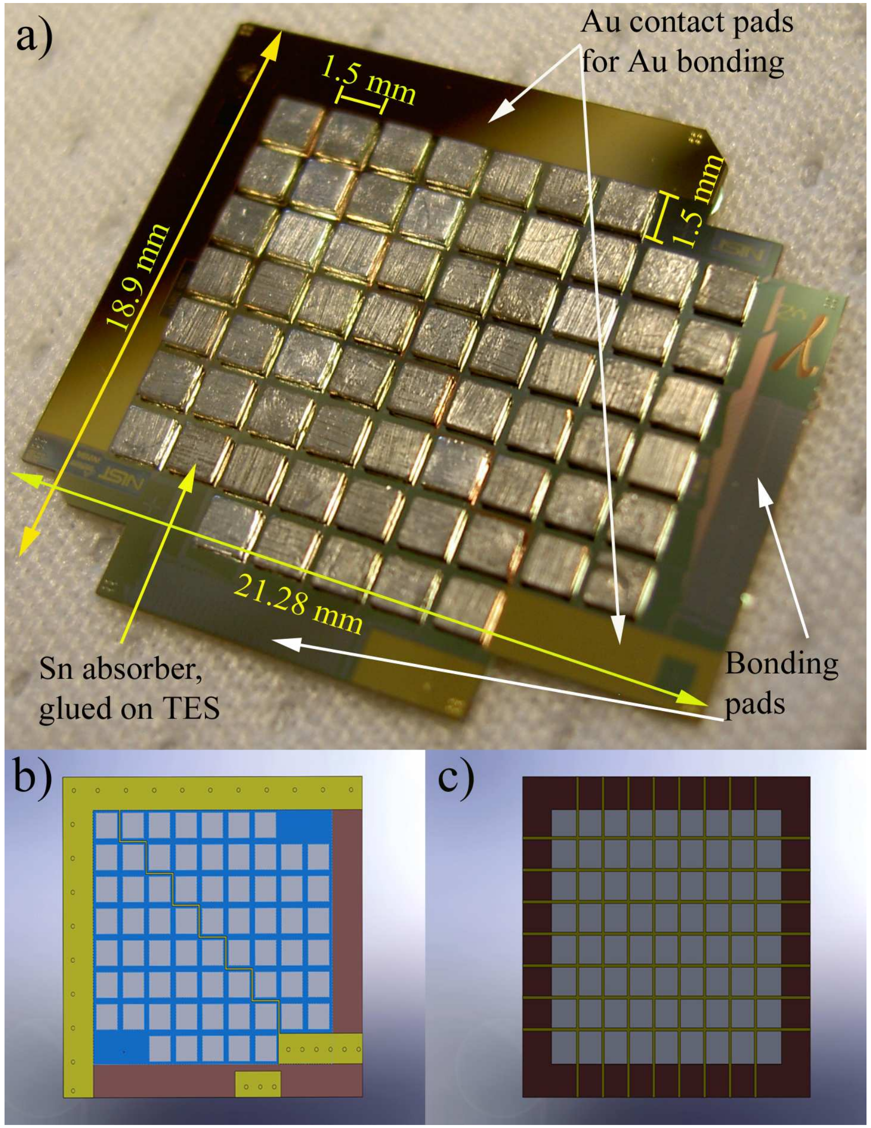
Things to improve:

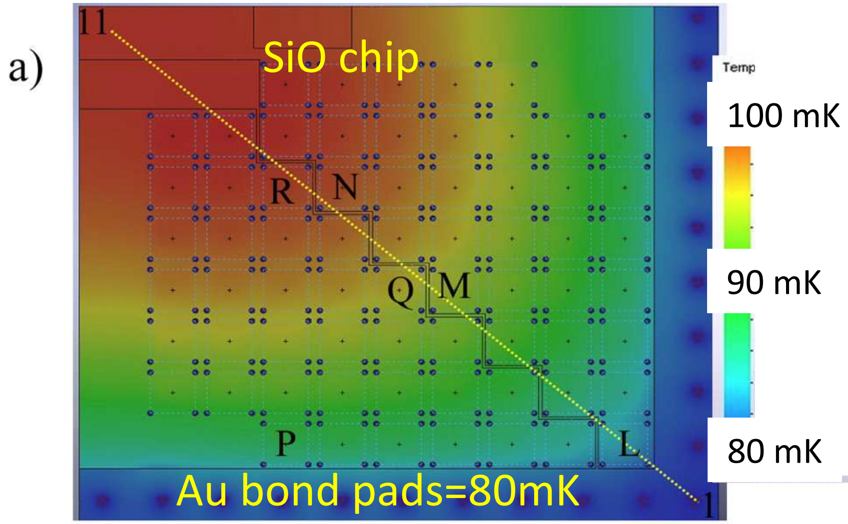
- Number of pixels (can be achieved by circuit inductance and bandwidth optimization).
- Energy Resolution.

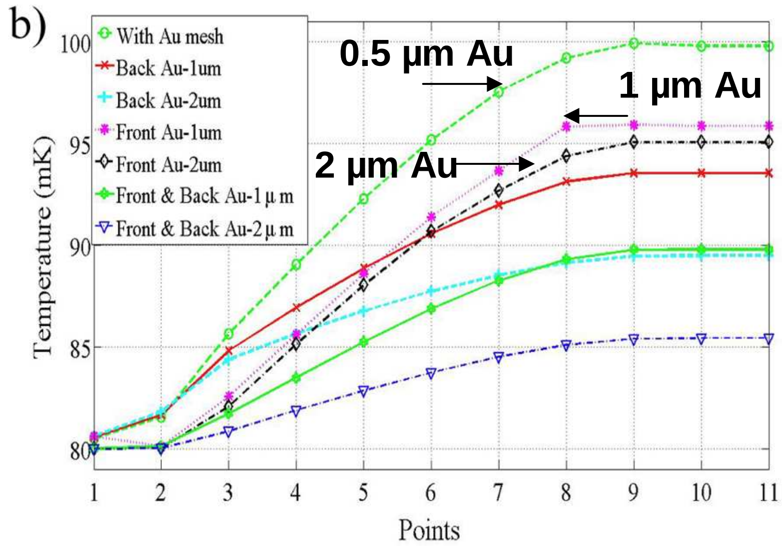
  Expected 70 eV, Achieved: 120 eV.

  →Thermal cross-talk between the pixels can degrade the energy resolution.

Application: γ-ray spectroscopy

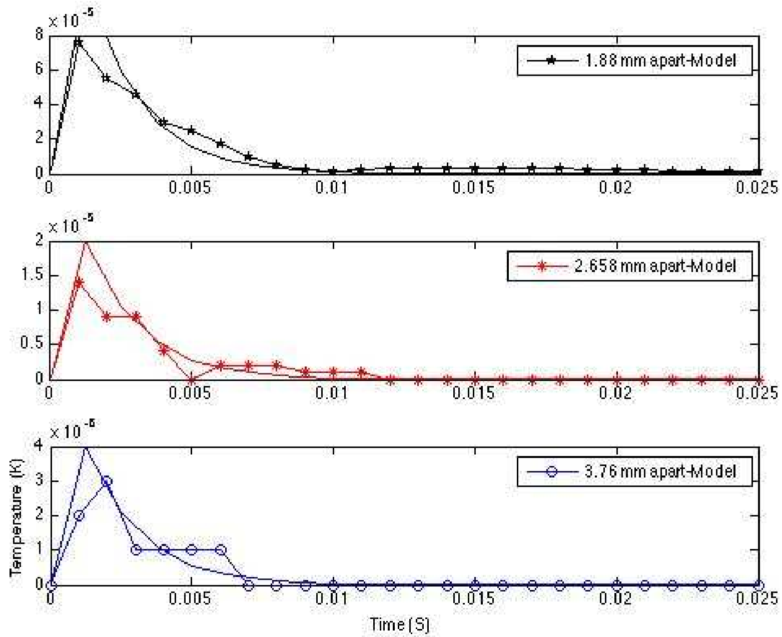






Thermal Cross-talk determination

- 2% thermal cross-talk in neighboring pixel.
- Better thermalization of chip should increase the resolution by 8-10 %.
- New chip is fabricated and is being tested at LANL.

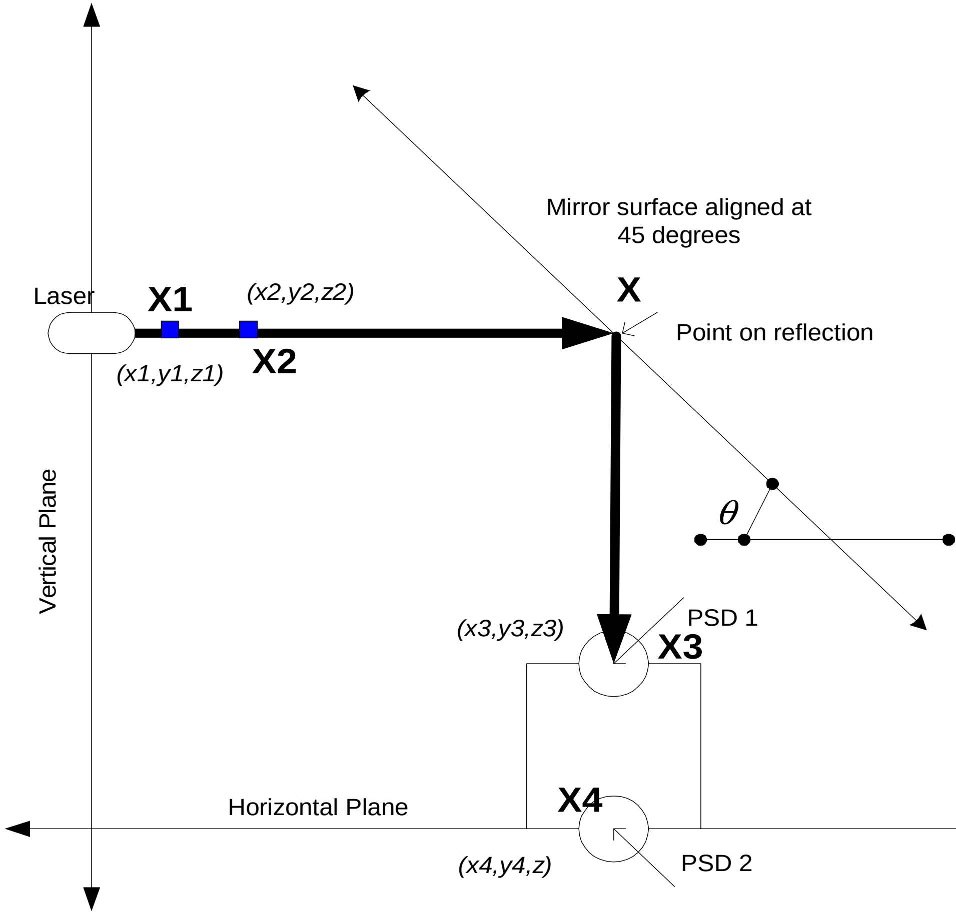


Current across TES (cross-talk)=

$$IFFT\left(Tsi(w).\frac{dT_{TES}}{dT_{SiO}}.\frac{dI(w)}{dT(w)}\right)$$

$$T(\rho,t)=\int \underbrace{2.(e^{(-t'/\tau_F)}-e^{(-t'/\tau_R)})}_{\text{Input heat pulse}}.\underbrace{\frac{E}{c}.\frac{e^{(-\rho^2/4D(t-t'))}.e^{(-\gamma.(t-t'))}}{4\pi Dc(t-t')}.dt'}_{\text{Heat flow in Si}}$$

Non-Contact Surface Measurment



$X = X1+(X2-X1) \times S$

$X = X3+(X4-X3) \times T$

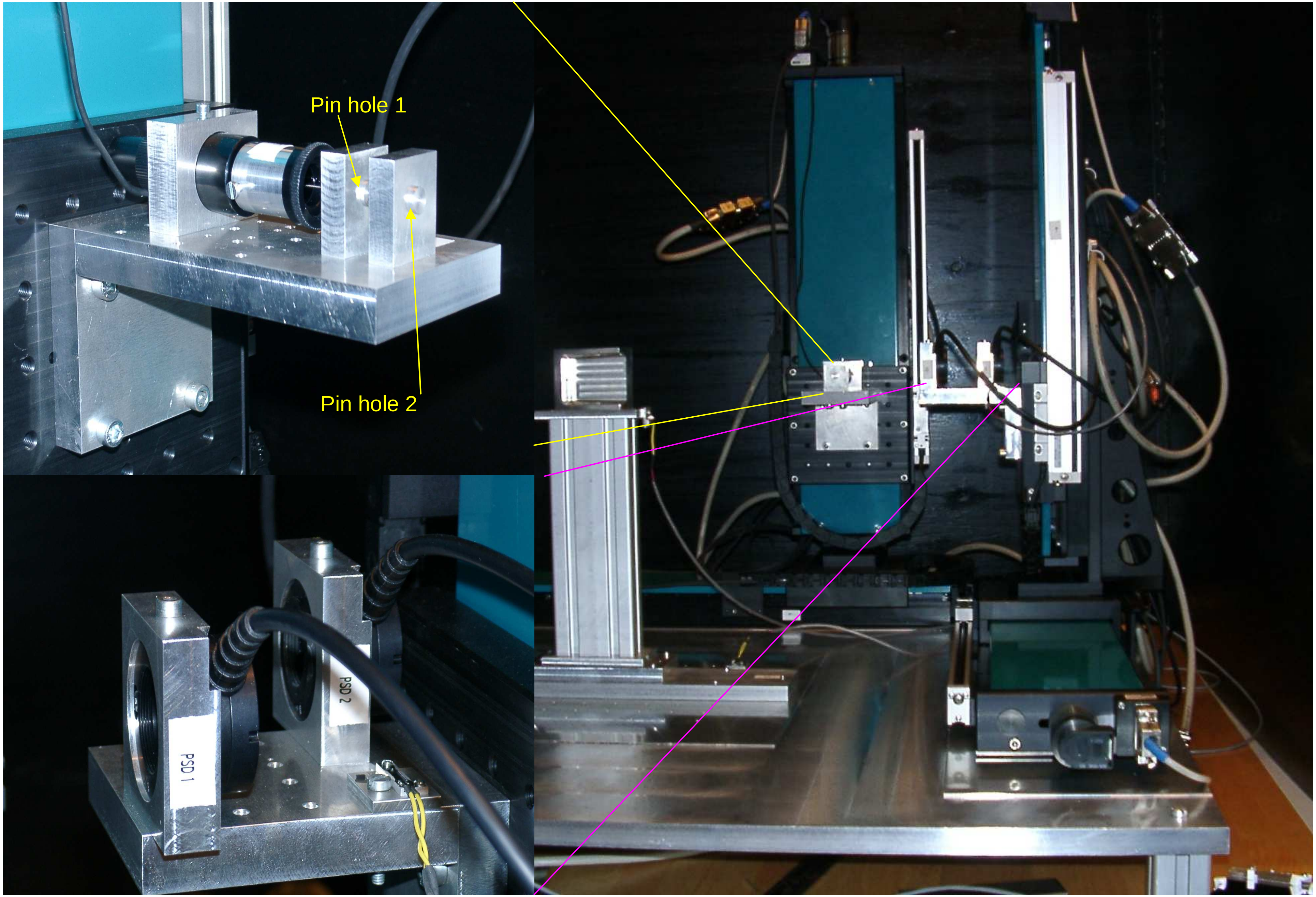
Skew Vector case:

$$D = \frac{\left|(x1 - x3)\cdot\left[(x2 - x1)\times(x4 - x3)\right]\right|}{\left|\left[(x2 - x1)\times(x4 - x3)\right]\right|}$$

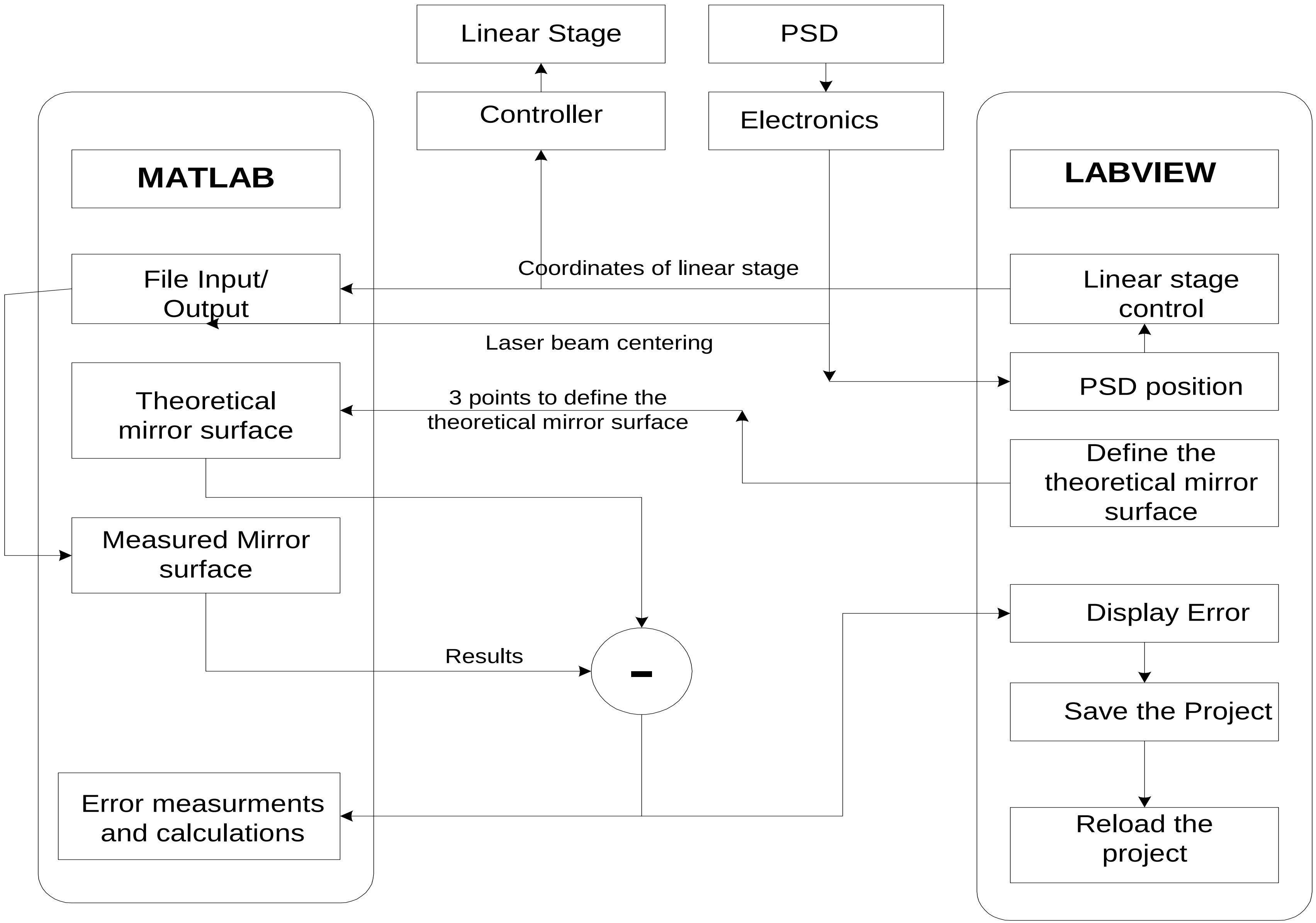
Perform this procedure to obtain 15 to 20 measured points on mirror surface

PSD: Position Sensitive Detector

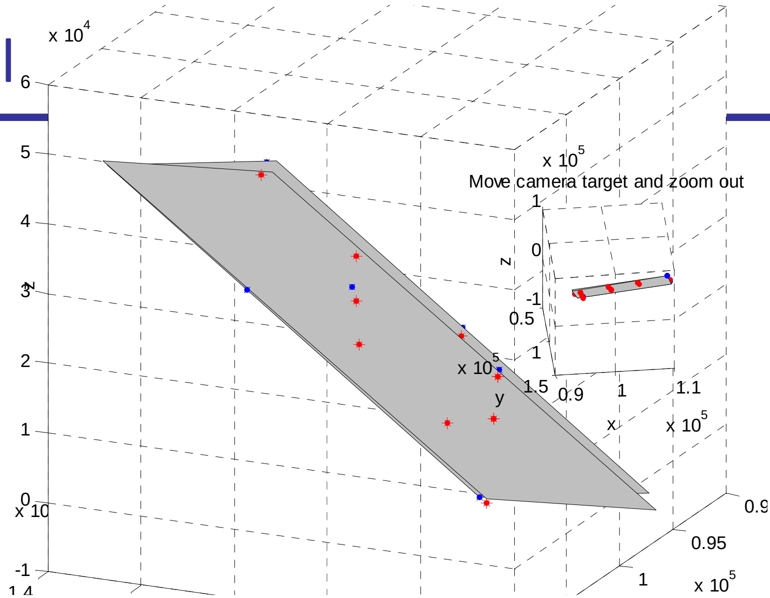
Optics Alignment Tool

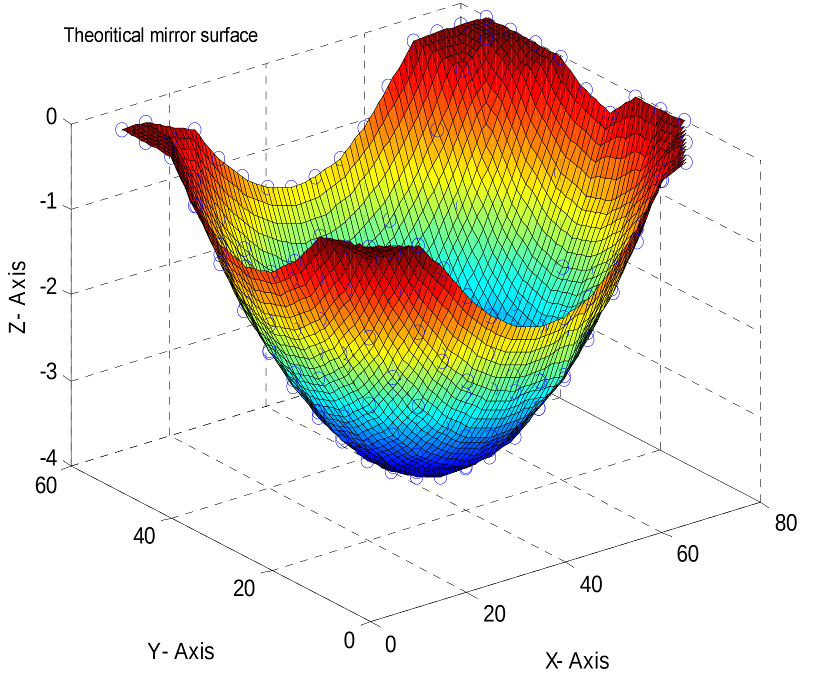


Optics Alignment Tool

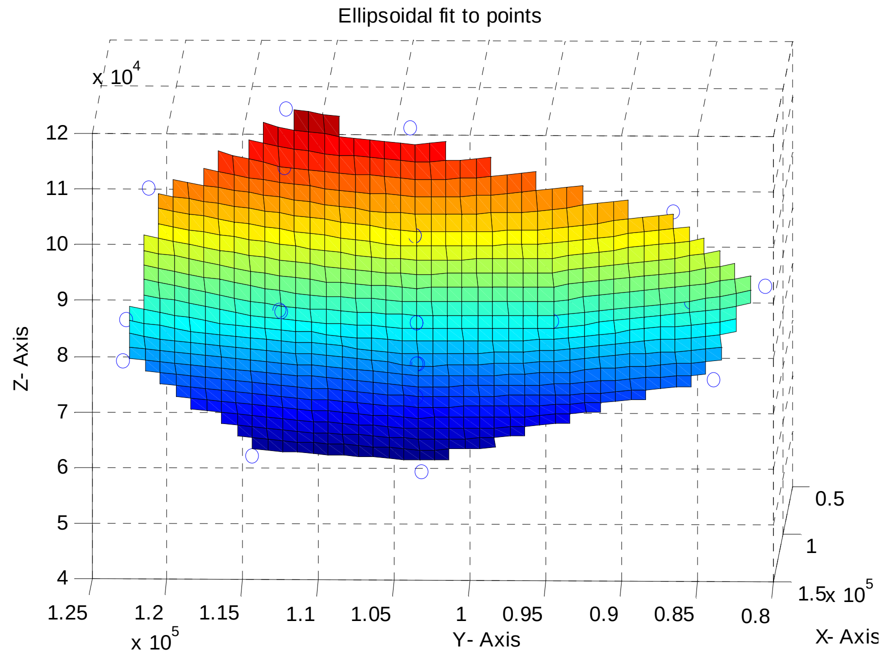


Optics Alignment Tool





Theoretical curved mirror



Observed curved mirror

Conclusions:

• Superconducting TES are the most sensitive detectors for millimeter-submillieter wavelength regime.

• Detectors successfully used for nuclear line forensics and spectroscopy → non-destructive analysis.

Personal gain:

• Ability to work on a project as a team member and individual.

• Knowledge of software and hardware.

• Lab-work, Cryostats, cryogens, instruments.

Everything has been very exciting and want to learn more.