High Spectral Resolution, High Cadence, Imaging X-ray Microcalorimeter Arrays for Solar Physics

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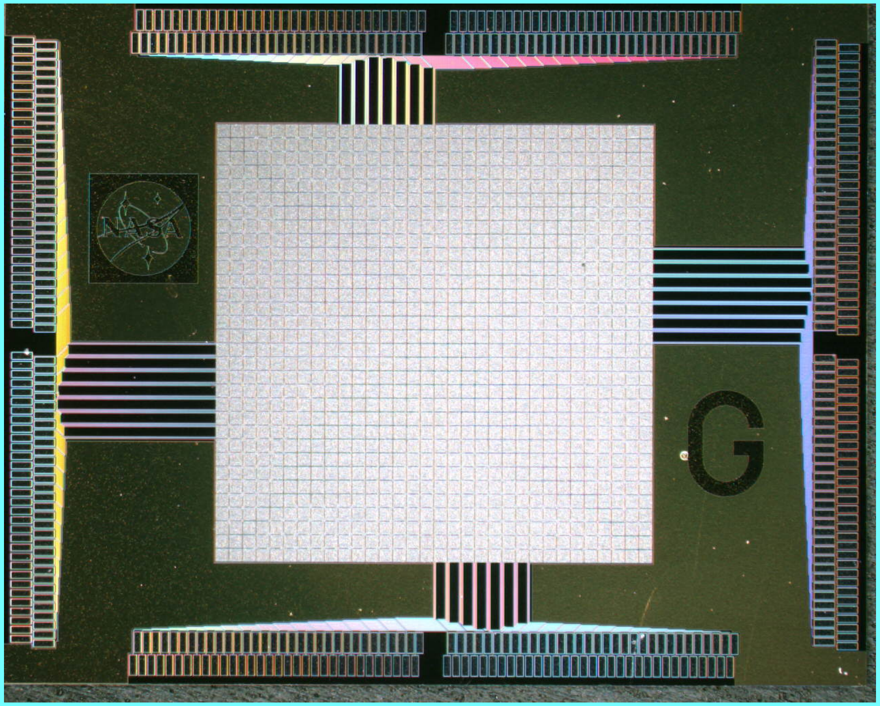
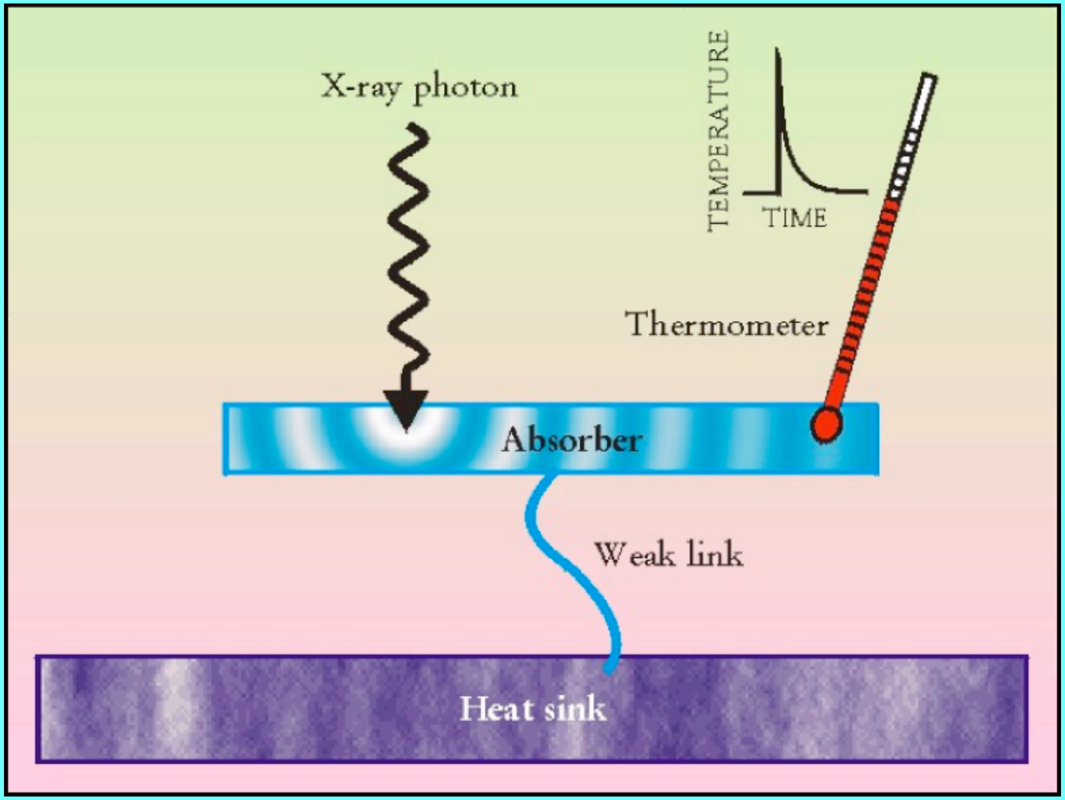
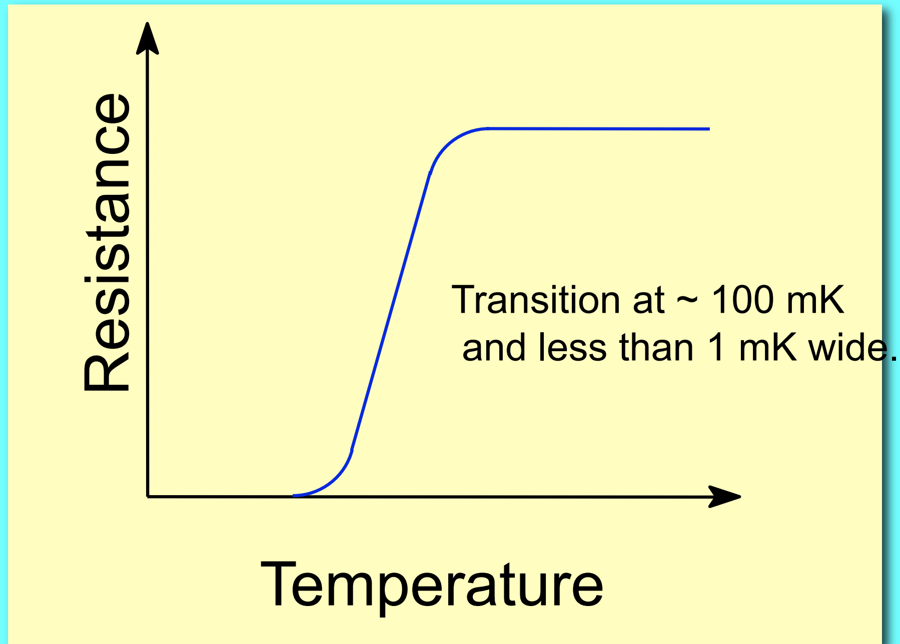
- Original motivation: RAM - Microcalorimeters to study dynamics & energetics of solar corona
- Continuing to develop microcalorimeter arrays potentially interesting for solar physics community
- Simultaneous imaging, spectroscopy & high cadence
- Pixels need to be *small* and *fast*



How do TES microcalorimeters work ?



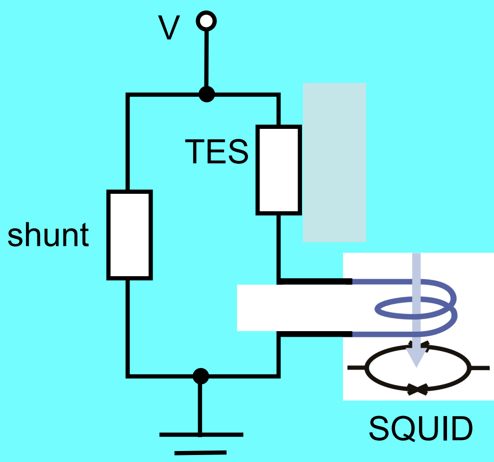


$$\delta T = \frac{E}{C_{\mathrm{tot}}}$$

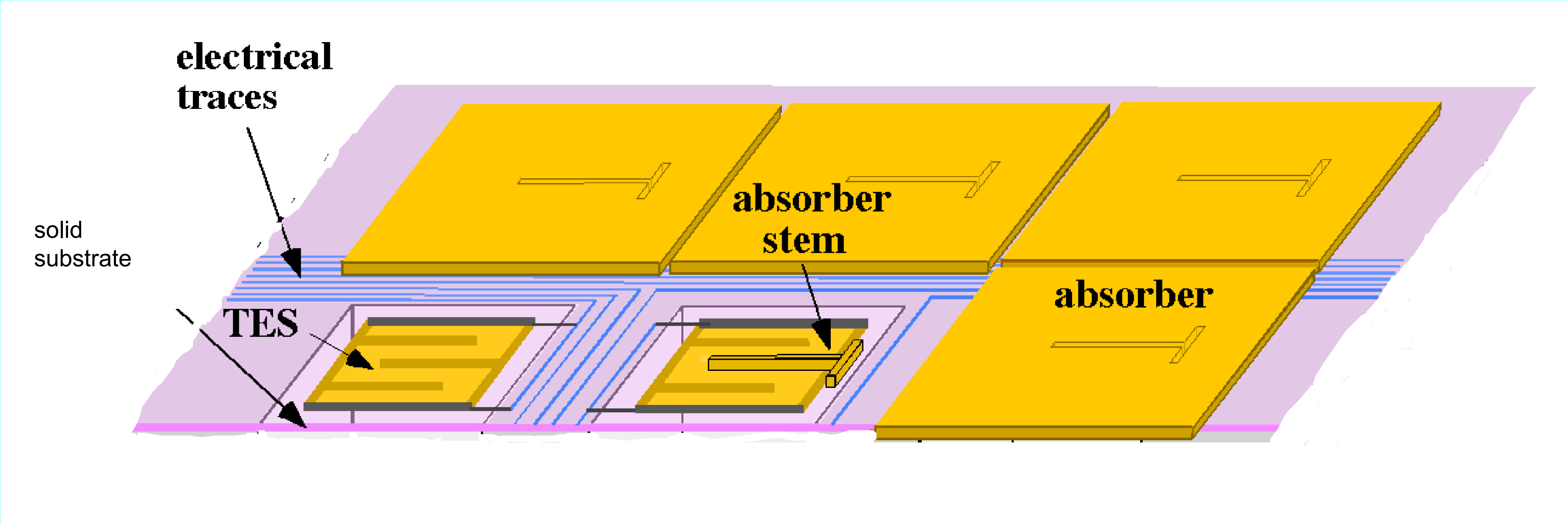
Thermal relaxation time:

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

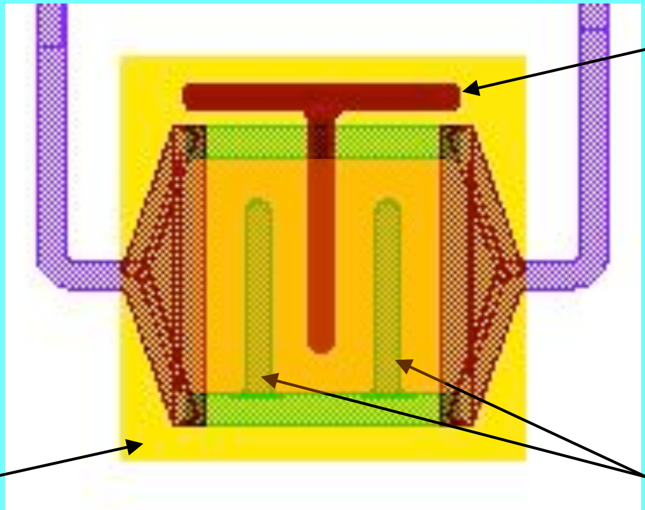
Thermal conductance



Solar TES microcalorimeters design : on solid substrate

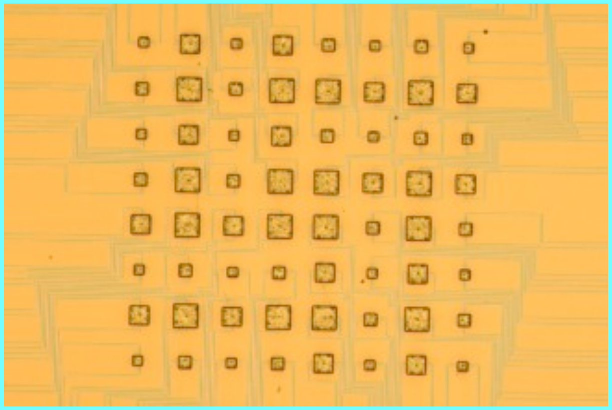
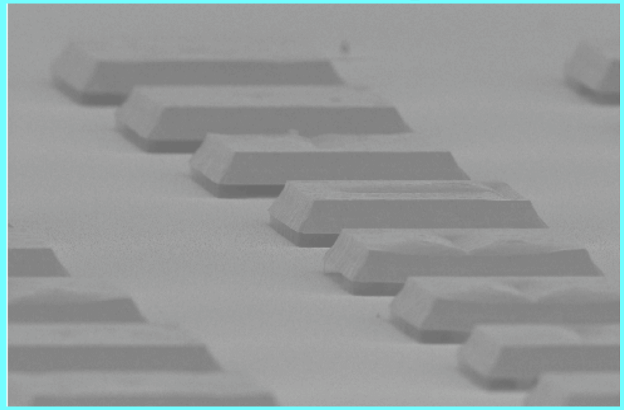
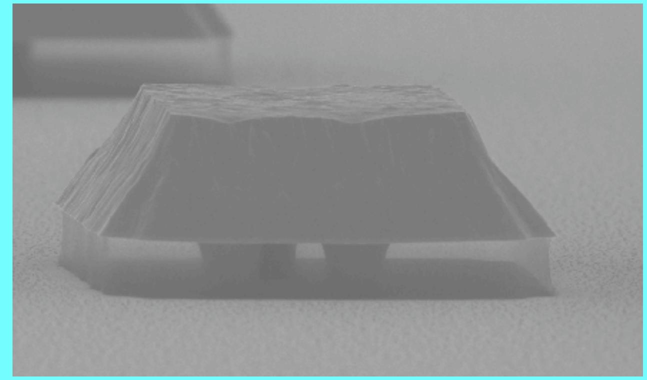
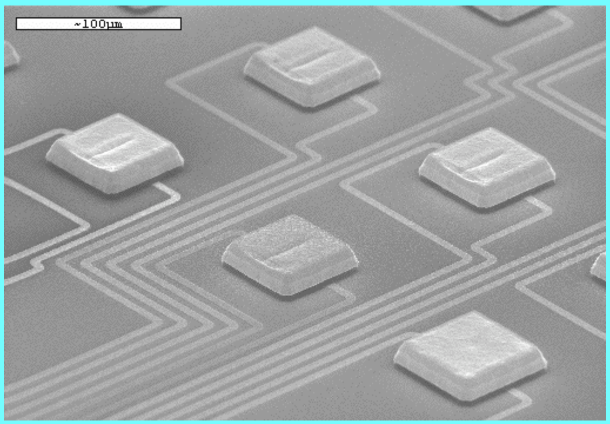
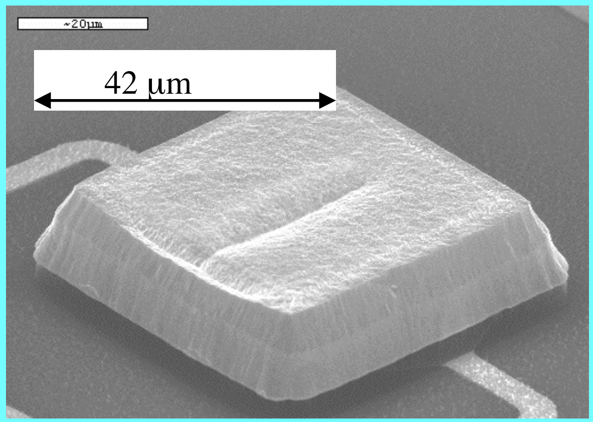


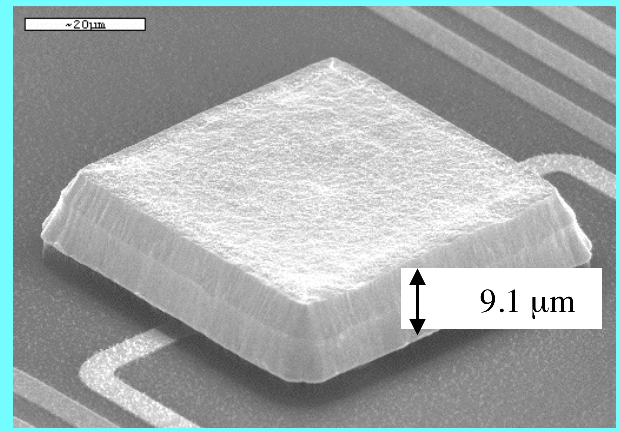
Pixel designs :



Thermal link (G): Kapitza

How small are the pixels ?

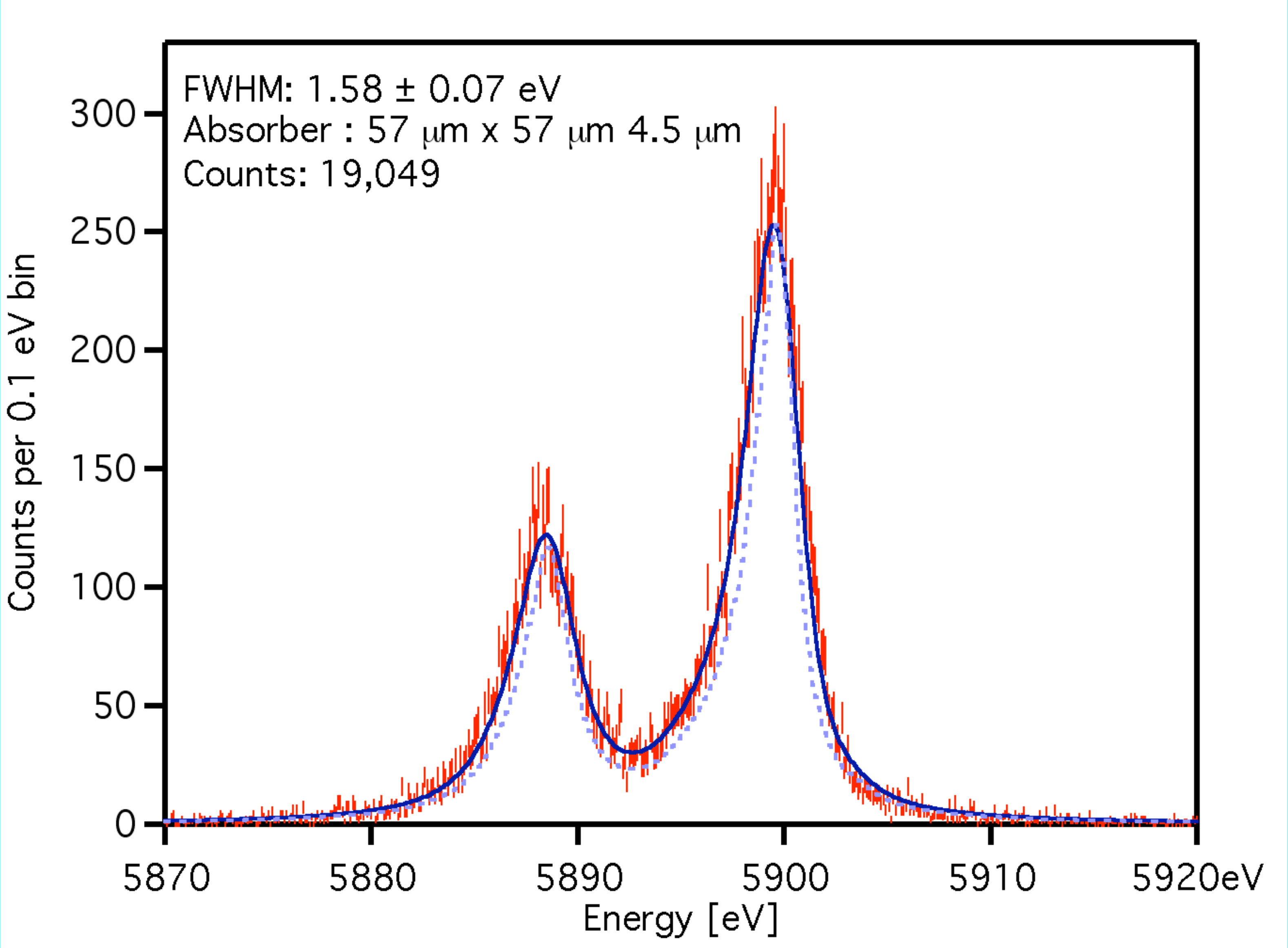








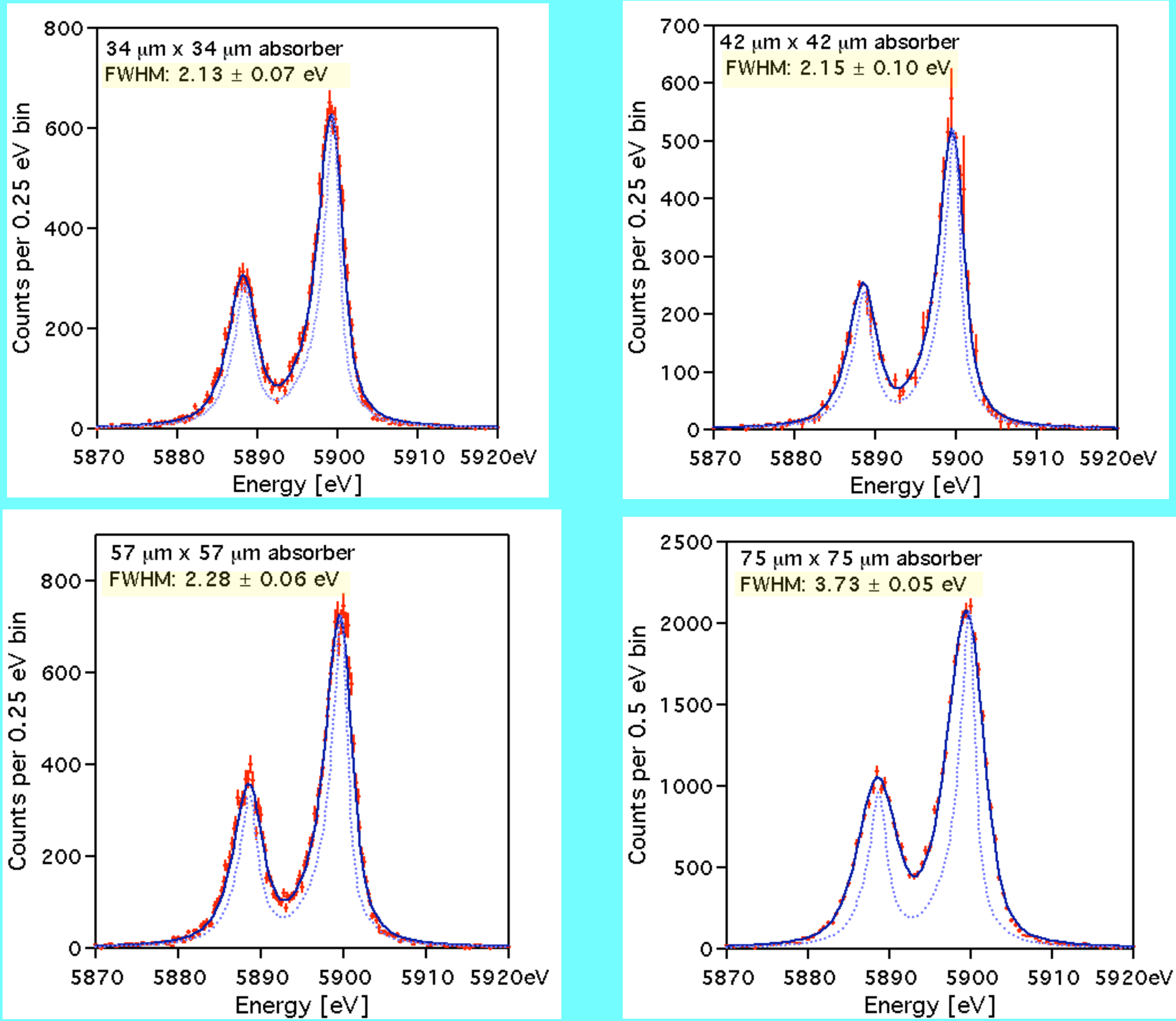
TES size	50 μm x 50 μm	35 μm x 35 μm	20 μm x 20 μm	12 μm x 12 μm
Absorber size	75 μm x 75 μm	57 μm x 57μm	42 μm x 42 μm	34 μm x 34 μm

Two gold thicknesses studied : 4.5 μm and 9.1 μm

What energy resolution is achievable ?

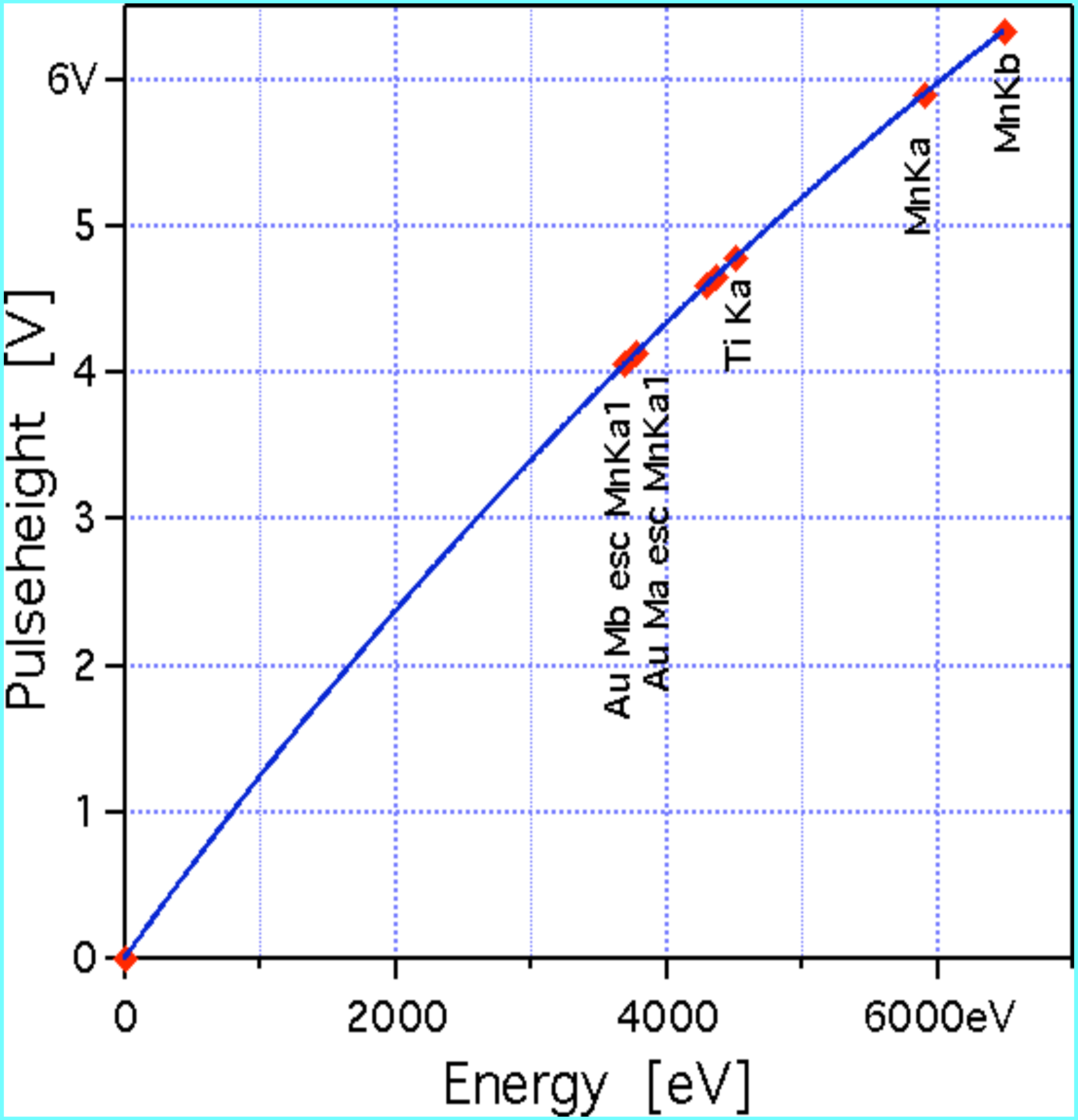


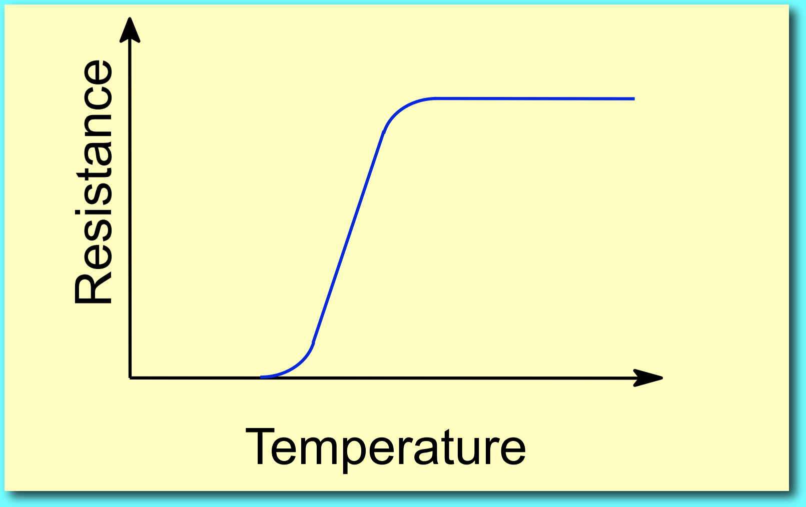
- Mn $K\alpha_1$ & $K\alpha_2$ x-rays at 6 keV from an ^{55}Fe internal conversion source
- Instrumental broadening consistent with a gaussian response with 1.58 eV resolution FWHM
- Baseline resolution : 1.1 eV (expected lower energy resolution)

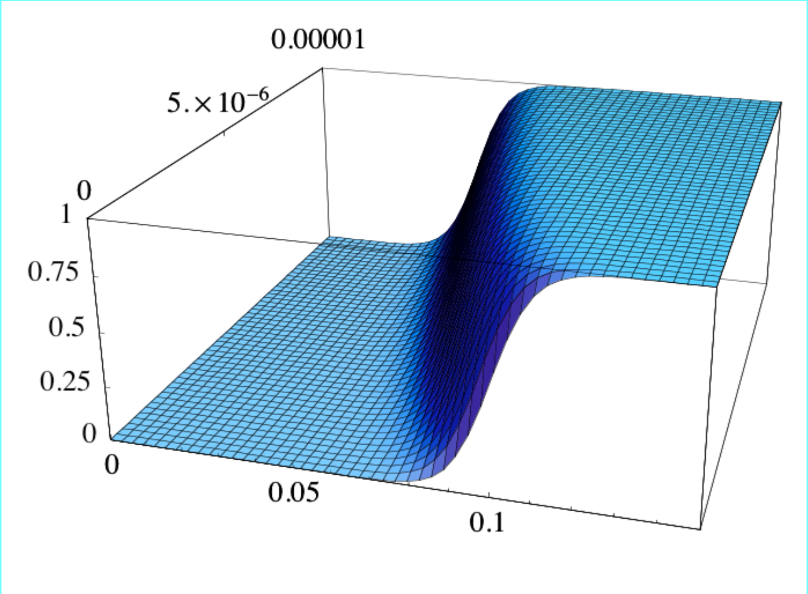


Absorber thickness : 9.1 μm. Heat bath temp. ~ 50 mK

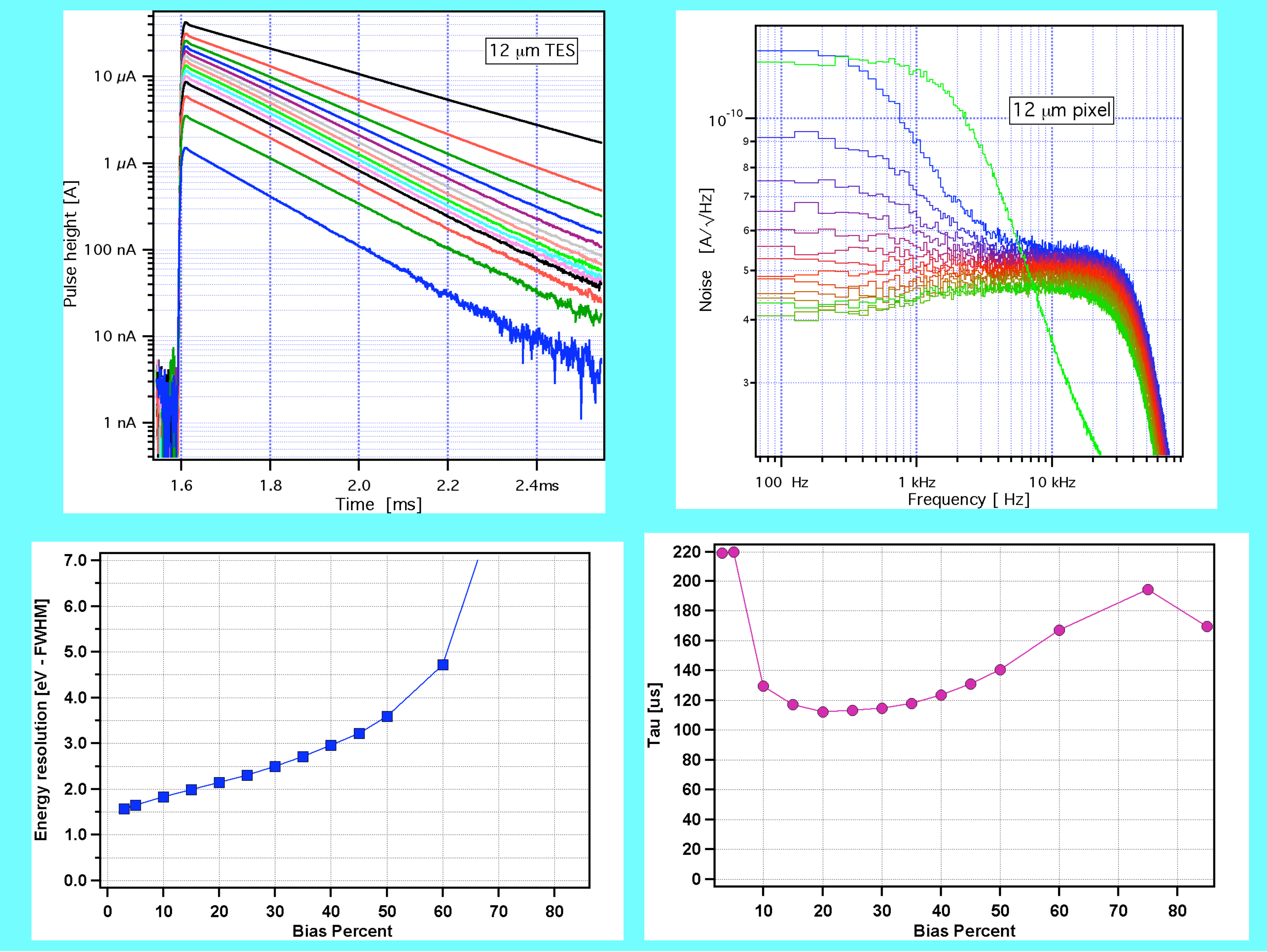
What is the linearity of the response like ?



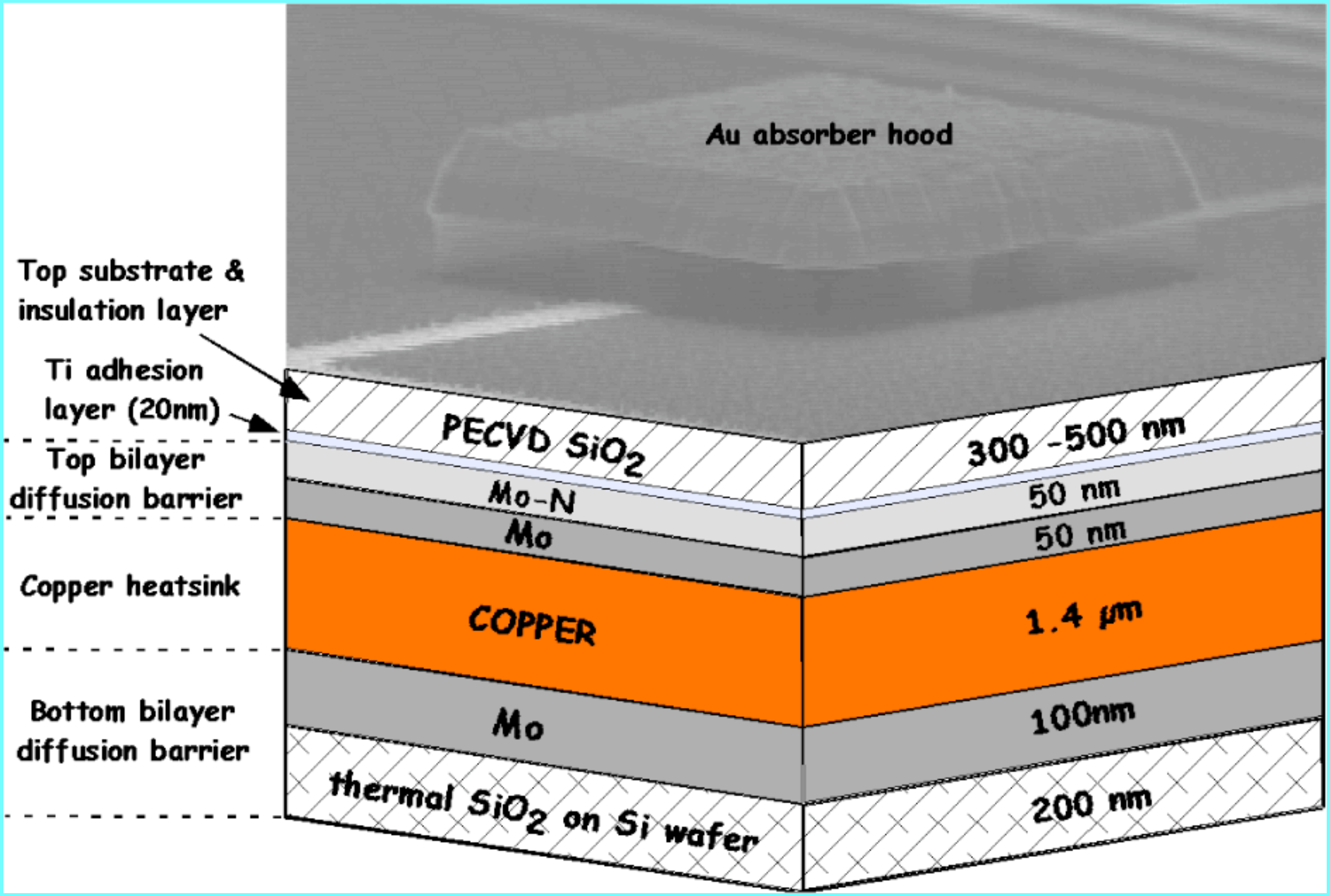




35 μm TES, 57 μm x 57 μm x 9 μm absorber


12 µm TES
Pulse height [A]
10 µA
1 µA
100 nA
10 nA
1 nA
1.6
1.8
2.0
2.2
2.4ms
Time [ms]
12 µm pixel
Noise [A/√Hz]
10^{-10}
100 Hz
1 kHz
10 kHz
Frequency [Hz]
Energy resolution [eV - FWHM]
Bias Percent
Tau [us]
Bias Percent

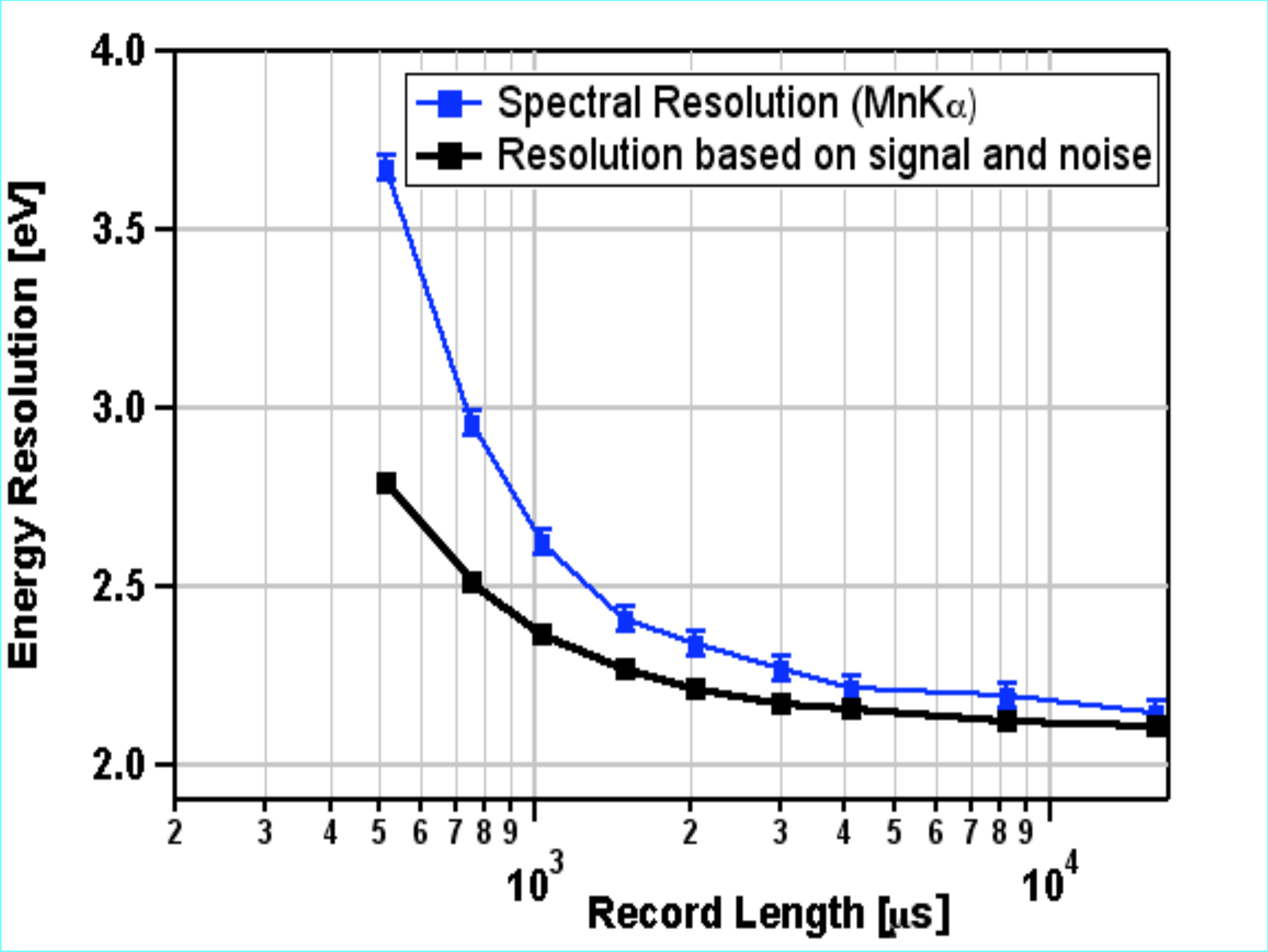
• Thermal ground plane - thermal cross-talk < 0.01% between nearest neighbors
• No collimation !!!
• Superconducting plane under TES removes all sensitivity to external magnetic fields



What count rates are achievable with high energy resolution ?

Optimal filtering :

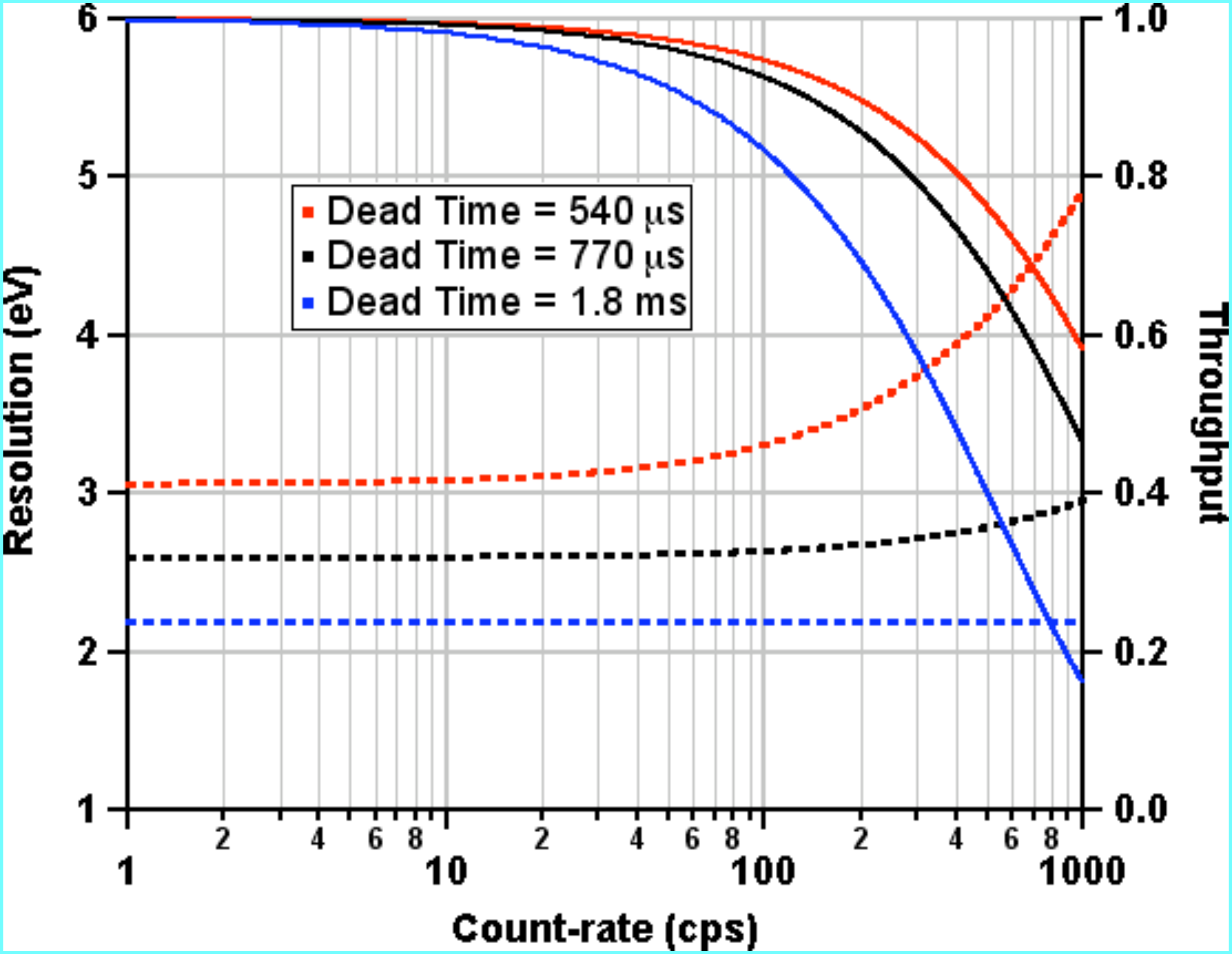
$$\Delta E_{rms} = \left(\int_0^\infty \frac{4\left|S(f)\right|^2}{\left\langle \left|N(f)\right|^2 \right\rangle} df \right)^{-1/2} = \left(\int_0^\infty \frac{4}{NEP(f)^2} df \right)^{-1/2}$$



35 μm device:

(The f=0 term in the optimal filter, which must be discarded, contains less info as record grows longer).

What count rates are achievable with high energy resolution ?



τ_{etf} = 210 μs

τ_c = 27 μs

Dead time = T1 + T2

T1: So not on tail of previous pulse

T2: Pulse record length for optimal filter

T1: = 9 $\tau_{c,}$ 10 $\tau_{c,}$ 12 τ_c

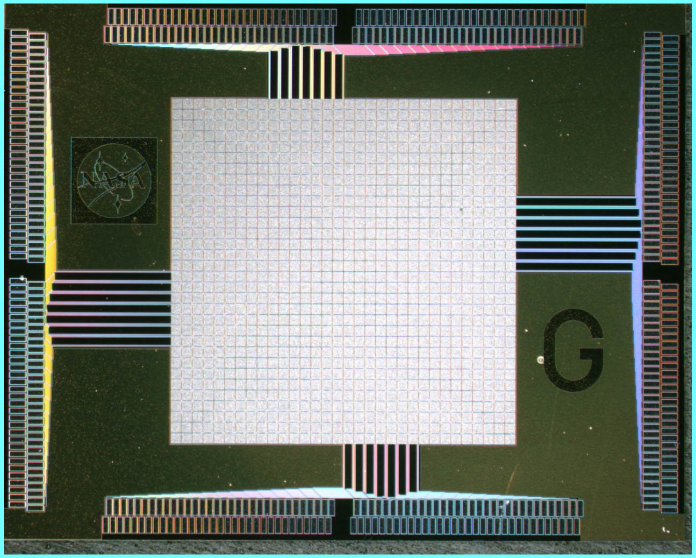
T2: = 300 μs, 500 μs and 1500 μs

Next : Close-pack arrays

TES size	Absorber Size	Gap with 75 μm pitch	Pitch of strip-line for 32x32 array
12 μm	34 μm x 34 μm	63 μm	~ 8 μm
20 μm	42 μm x 42 μm	50 μm	~ 6 μm
35 μm	57 μm x 57 μm	40 μm	~ 5 μm
50 μm	75 μm x75 μm	25 μm	~ 3 μm

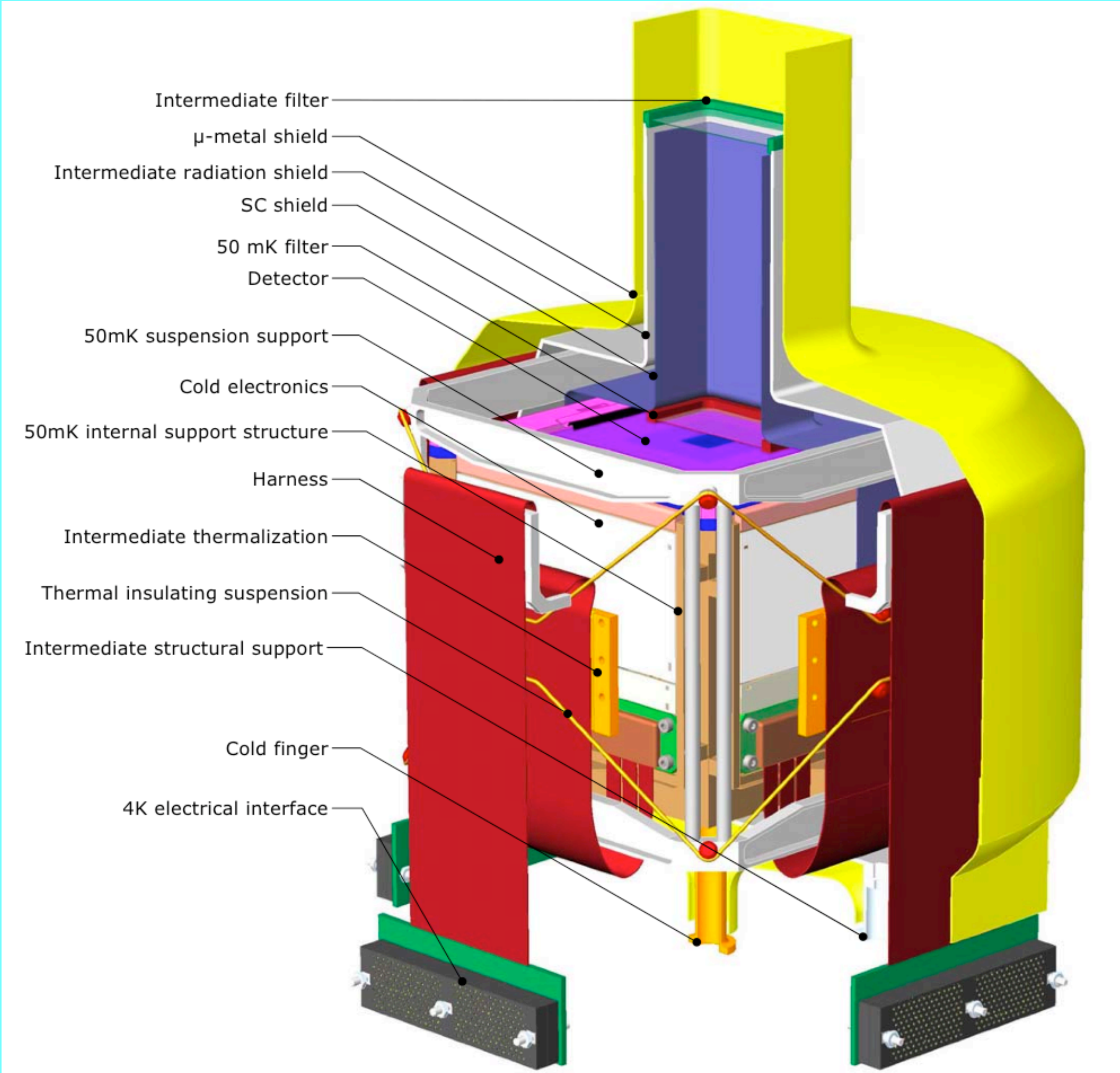
~ N/4 wire pairs per muntin for NXN array
8 wire pairs for 32 x 32 array

(More exactly : $(N-2)^2$ / $(4*(N-3))$,
– goes to N/4 for large N)

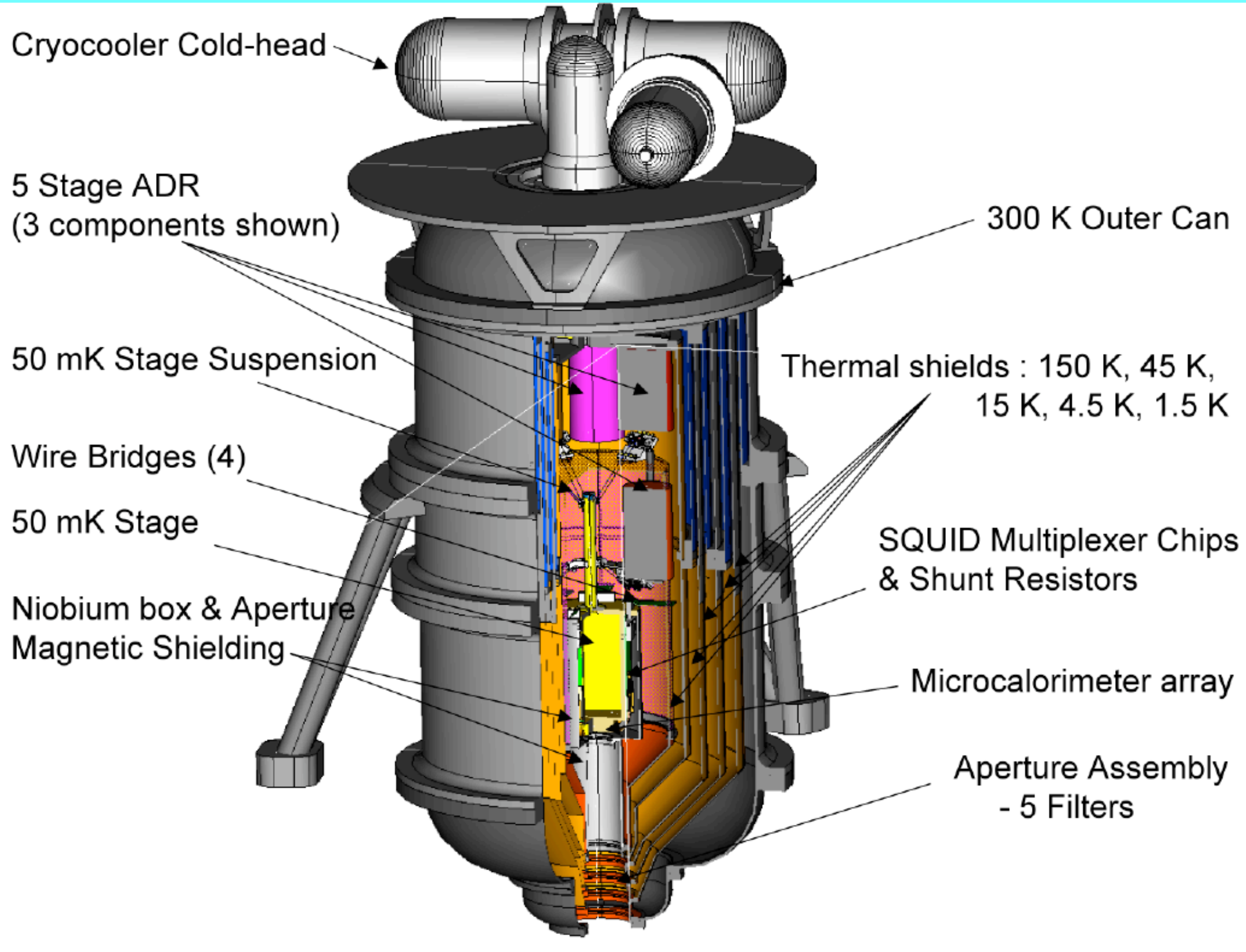


Prototype IXO 32x32 array

Plans : Build 8x8, 32x32, 64x64 arrays of close-packed pixels

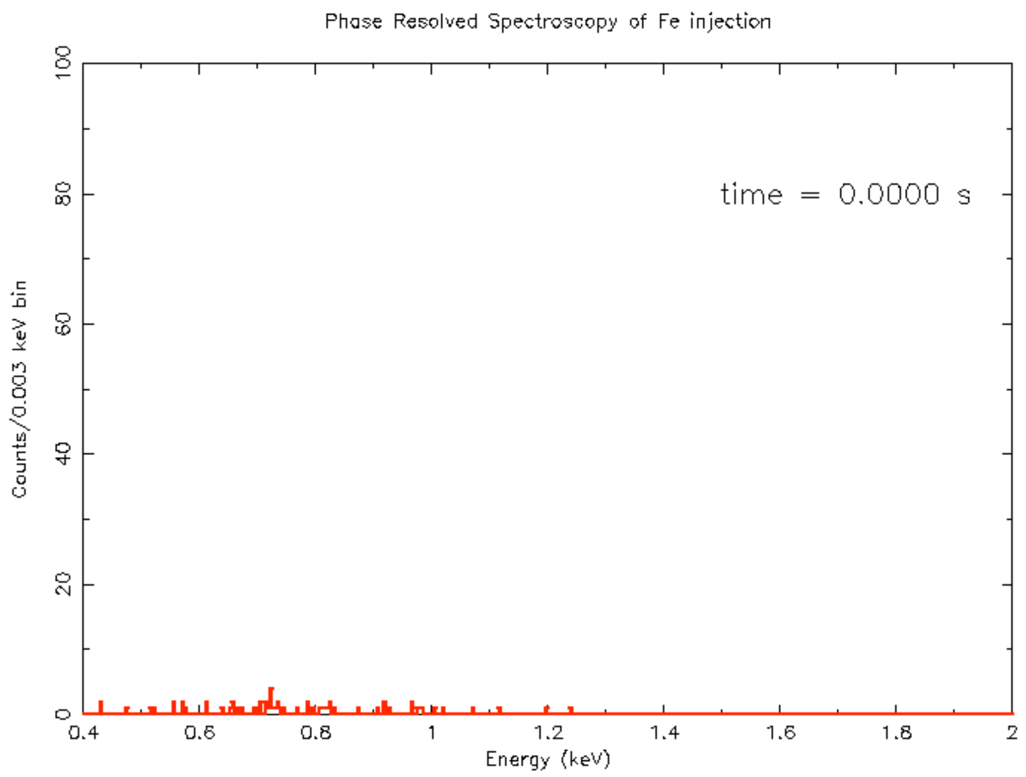


Intermediate filter
μ-metal shield
Intermediate radiation shield
SC shield
50 mK filter
Detector
50mK suspension support
Cold electronics
50mK internal support structure
Harness
Intermediate thermalization
Thermal insulating suspension
Intermediate structural support
Cold finger
4K electrical interface


Cryocooler Cold-head
5 Stage ADR
(3 components shown)
50 mK Stage Suspension
Wire Bridges (4)
50 mK Stage
Niobium box & Aperture
Magnetic Shielding
300 K Outer Can
Thermal shields : 150 K, 45 K,
15 K, 4.5 K, 1.5 K
SQUID Multiplexer Chips
& Shunt Resistors
Microcalorimeter array
Aperture Assembly
- 5 Filters

Why X-ray microcalorimeters for solar physics ?

- Detect & resolve hundreds of atomic transition lines from different ionization states of many elements in the solar atmosphere
- Determine the abundances of elements from carbon to nickel relative to hydrogen
- Determine thermal & non-thermal electron distributions from both lines & continuum
- Determine plasma densities ~ 10^9 - 10^{14} cm^{-3}, temps from < 0.7 to >10 million degrees
- Detect flows with velocities down to < 50 km/s
- Precision timing of photons from flares



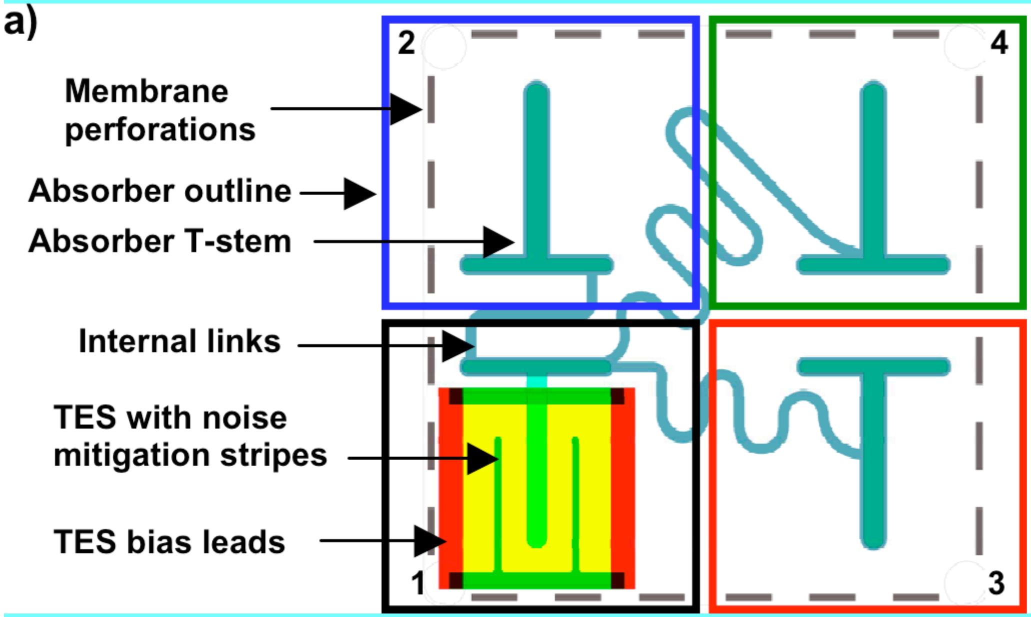
Electron energy = 4.1 keV
Electron density ~$10^{12}/cm^3$.

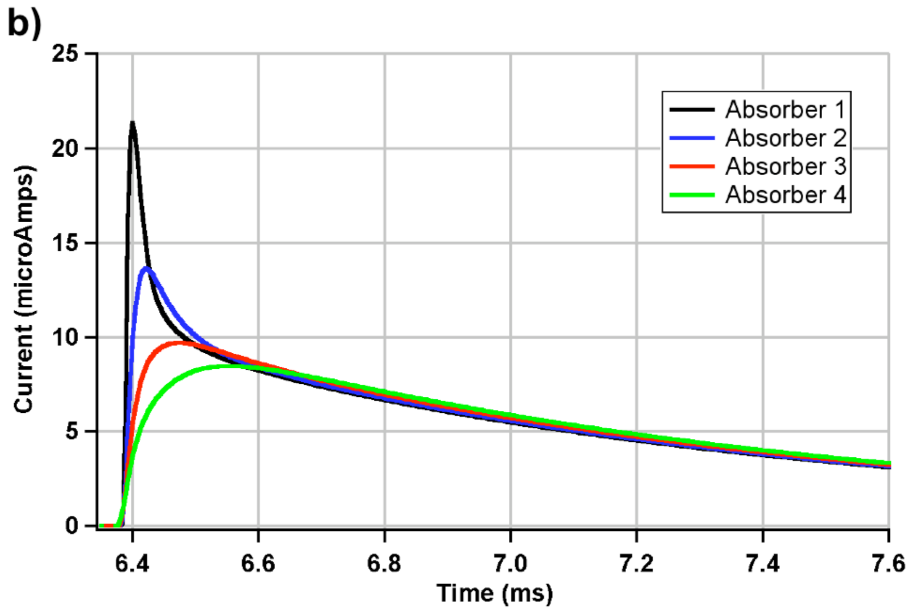
- Ionization state not in equilibrium with electron energy.

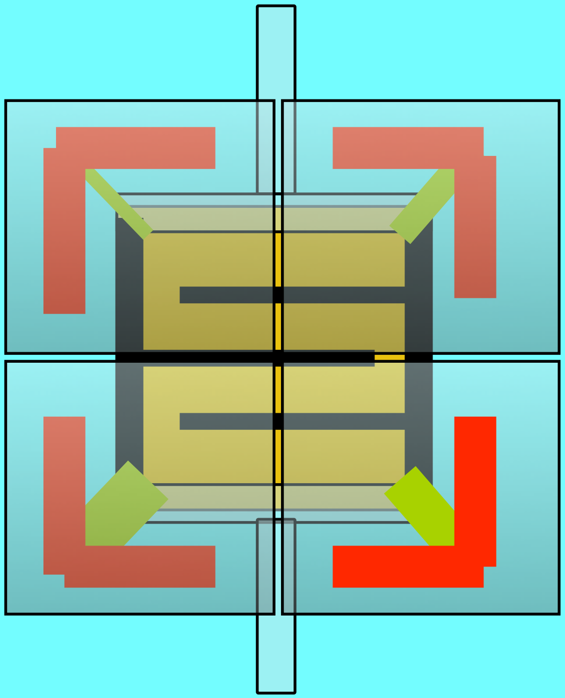
- The Fe ionizes extremely rapidly to Fe XVII

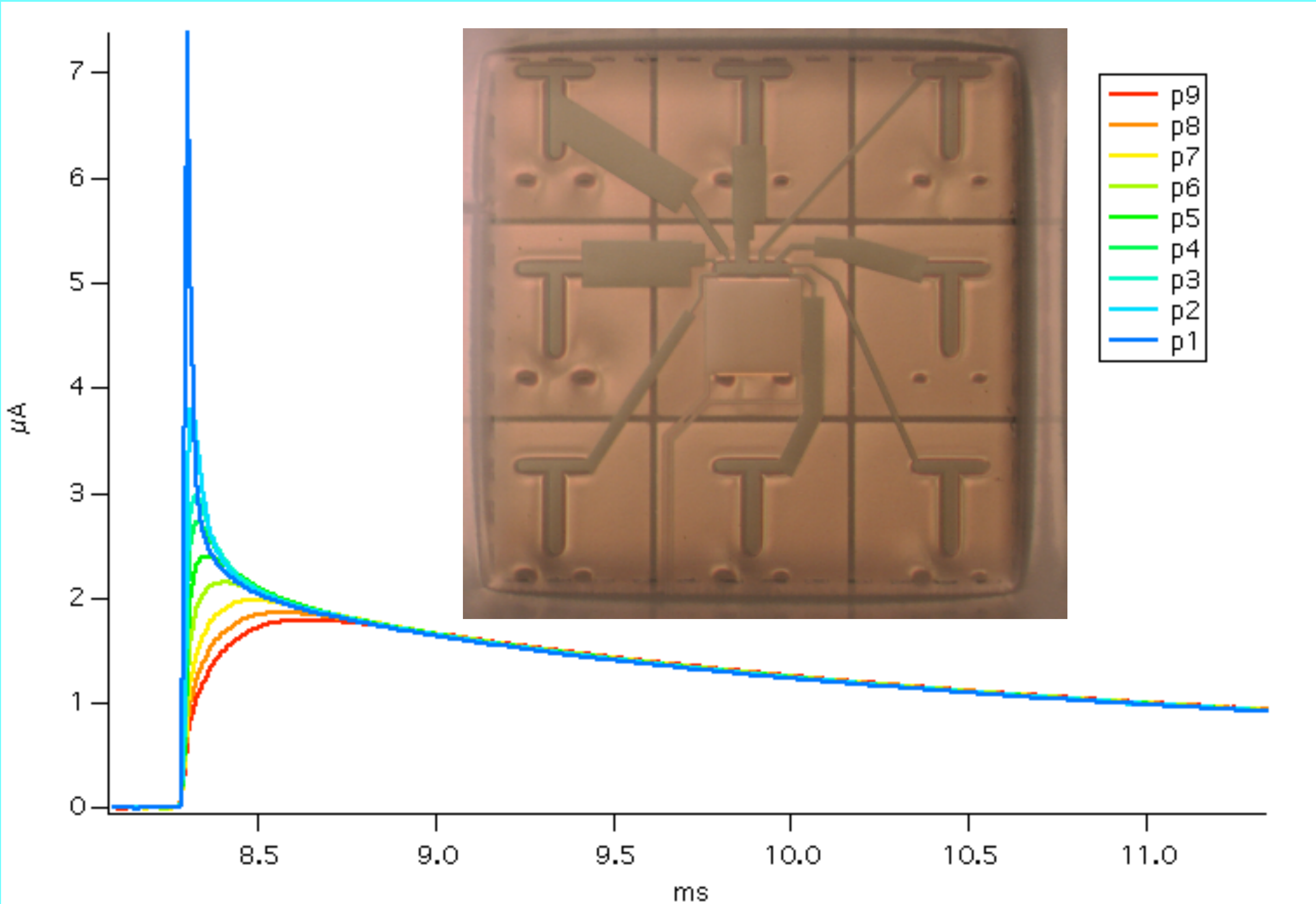
- Ionization evolves from mostly slowly XVII/XVIII to an intermediate state with all ionization states from XVII-XXIV and then comes into equilibrium (mostly Fe XXIII / XXIV)

Increasing the FOV ..... one possibility :



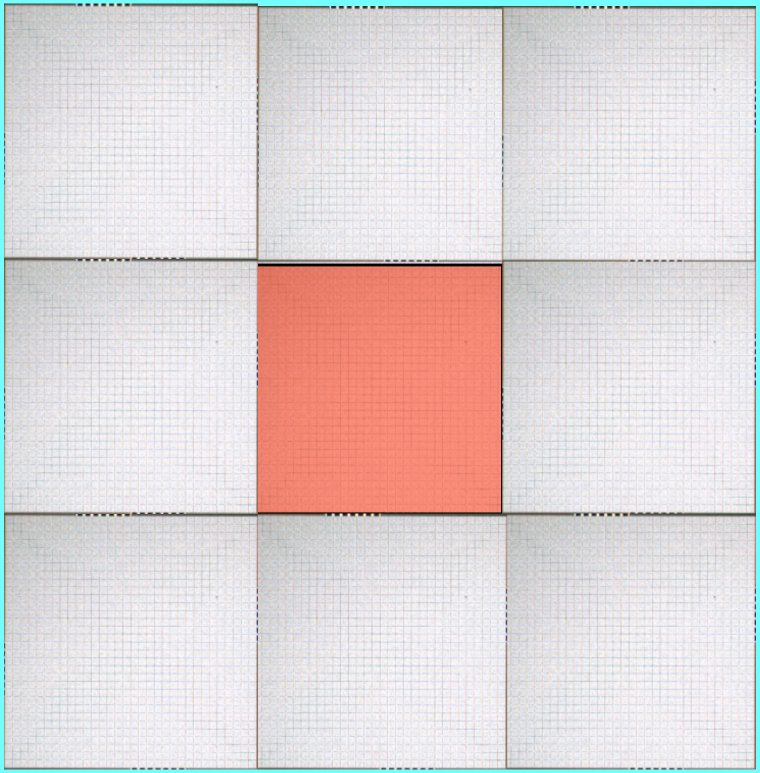






μA
0
1
2
3
4
5
6
7
8.5
9.0
9.5
10.0
10.5
11.0
ms
p9
p8
p7
p6
p5
p4
p3
p2
p1

Strawman Solar Instrument Design :



Focal plane hybrid inner & outer array

Inner array : 32x32 array, pitch of 75 μm (1024 pixels).

Outer array : 1024 TESs, each TES has 9 absorbers attached (same plate scale as inner array (9216 absorbers).

This gives a total of 10,240 absorbers (pixels) ~ 100x100 array.

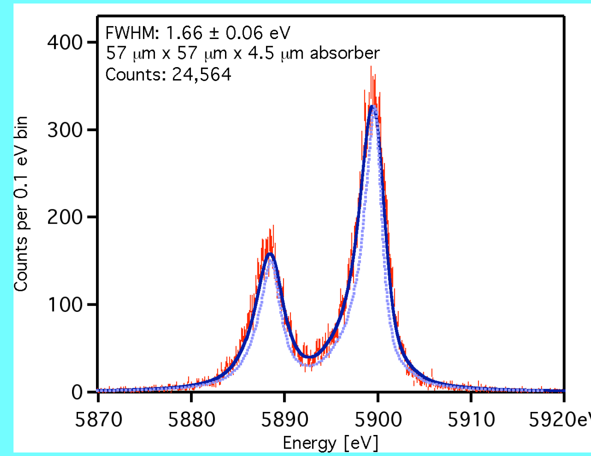
Read out using 64 multiplexing amplifier channels (each reading out 32 TES sensors).

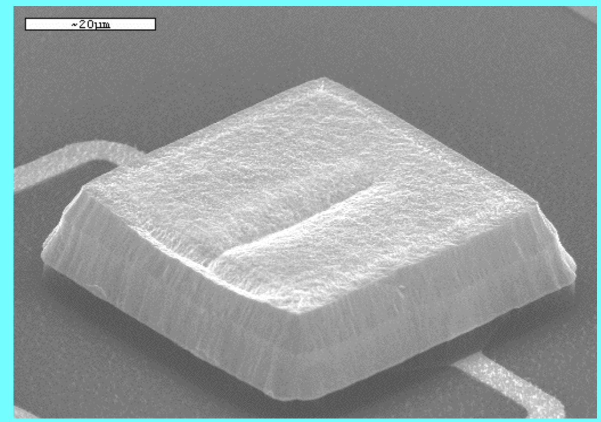
For focal length = 7.7 meters, each pixel is 2”, FOV is 3.3'x3.3'.

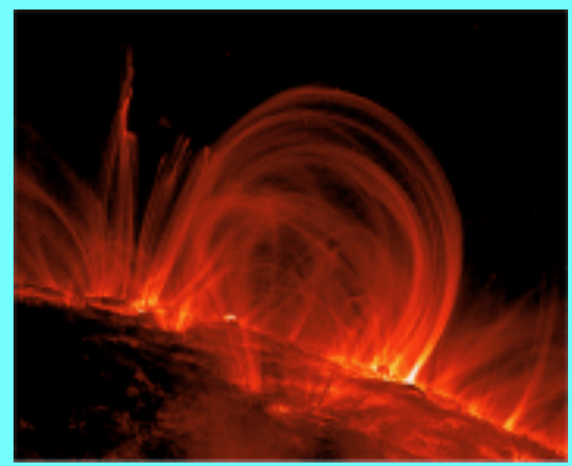
For focal length = 15.4 meters, each pixel is 1”, FOV is 1.7'x1.7'.

Conclusions:

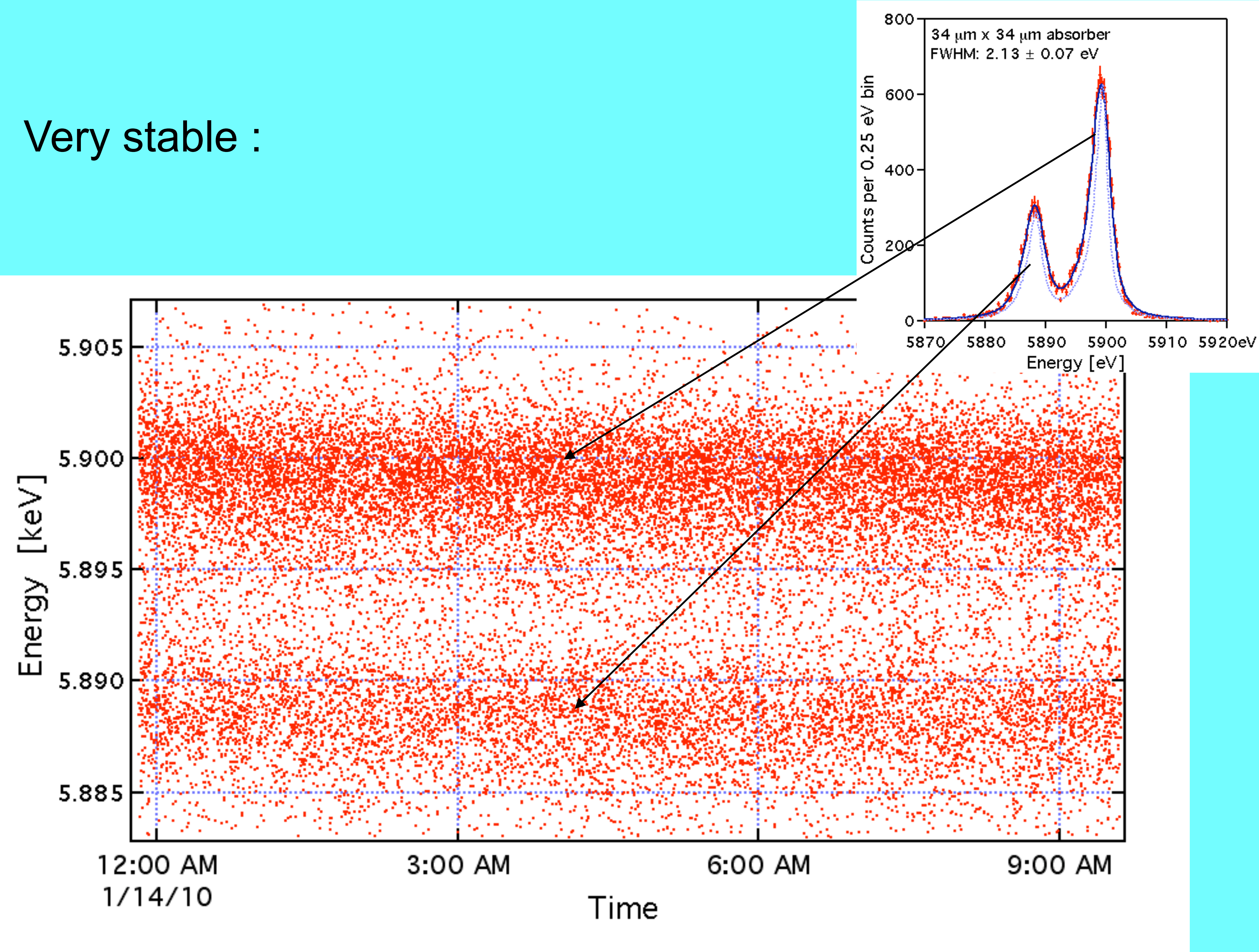
- Excellent energy resolution achieved in small, low heat capacity x-ray microcalorimeters < 2 eV
- Count rates > 300 cps achievable
- Design suitable for solar physics
- Let's work together - we welcome participation in development of instrument/science from solar plasma spectroscopists !



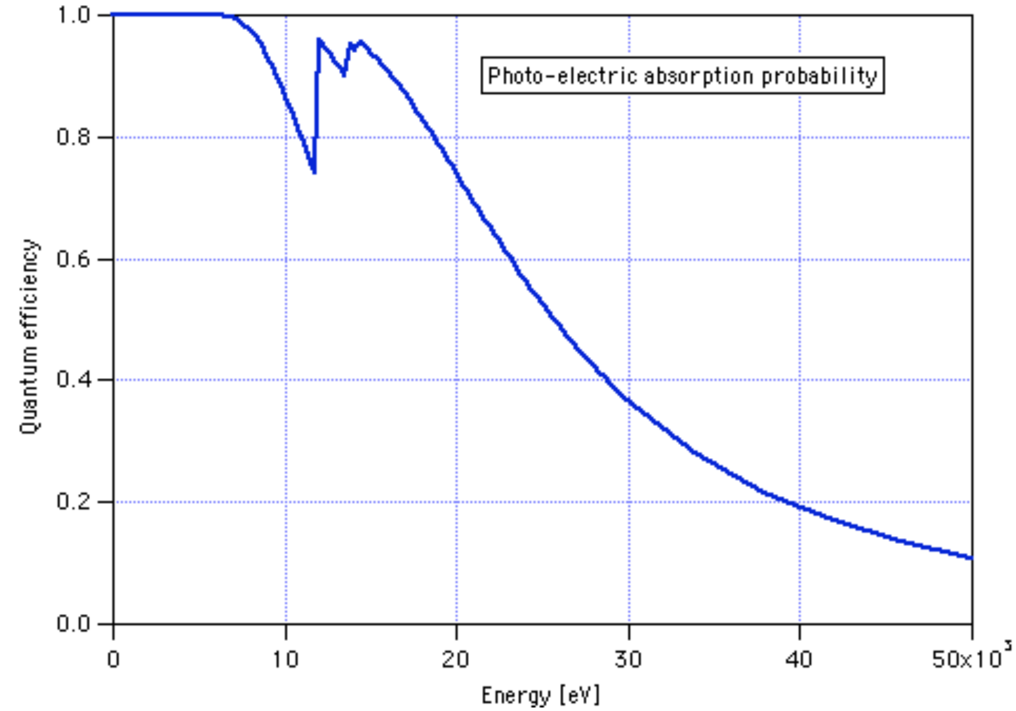




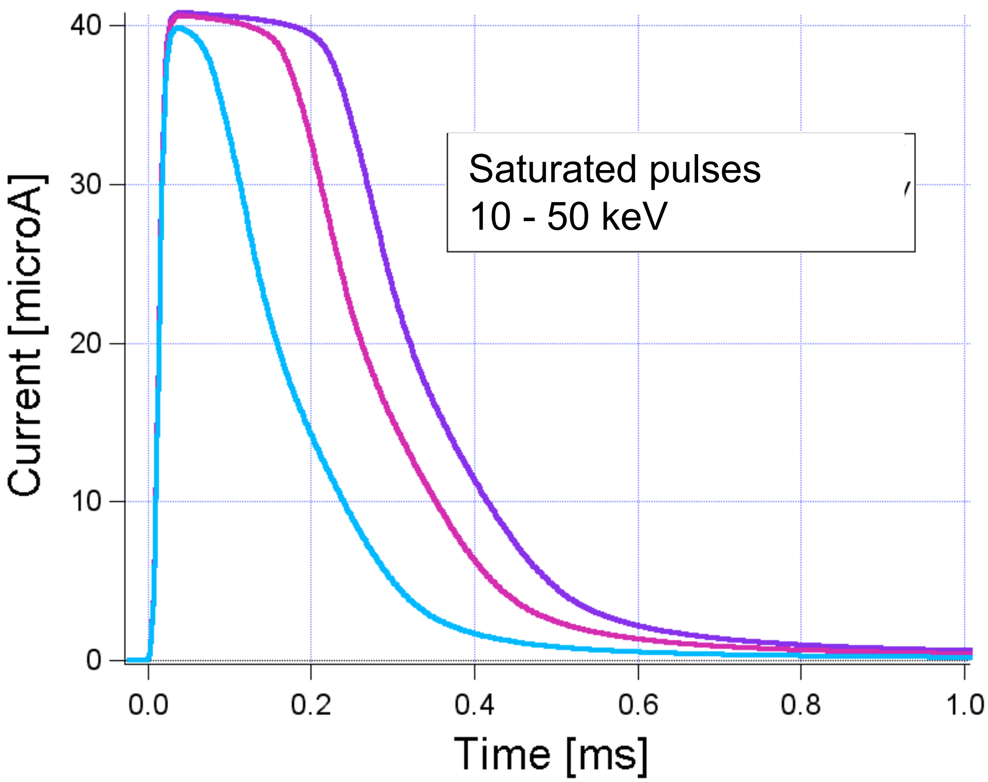
Very stable :

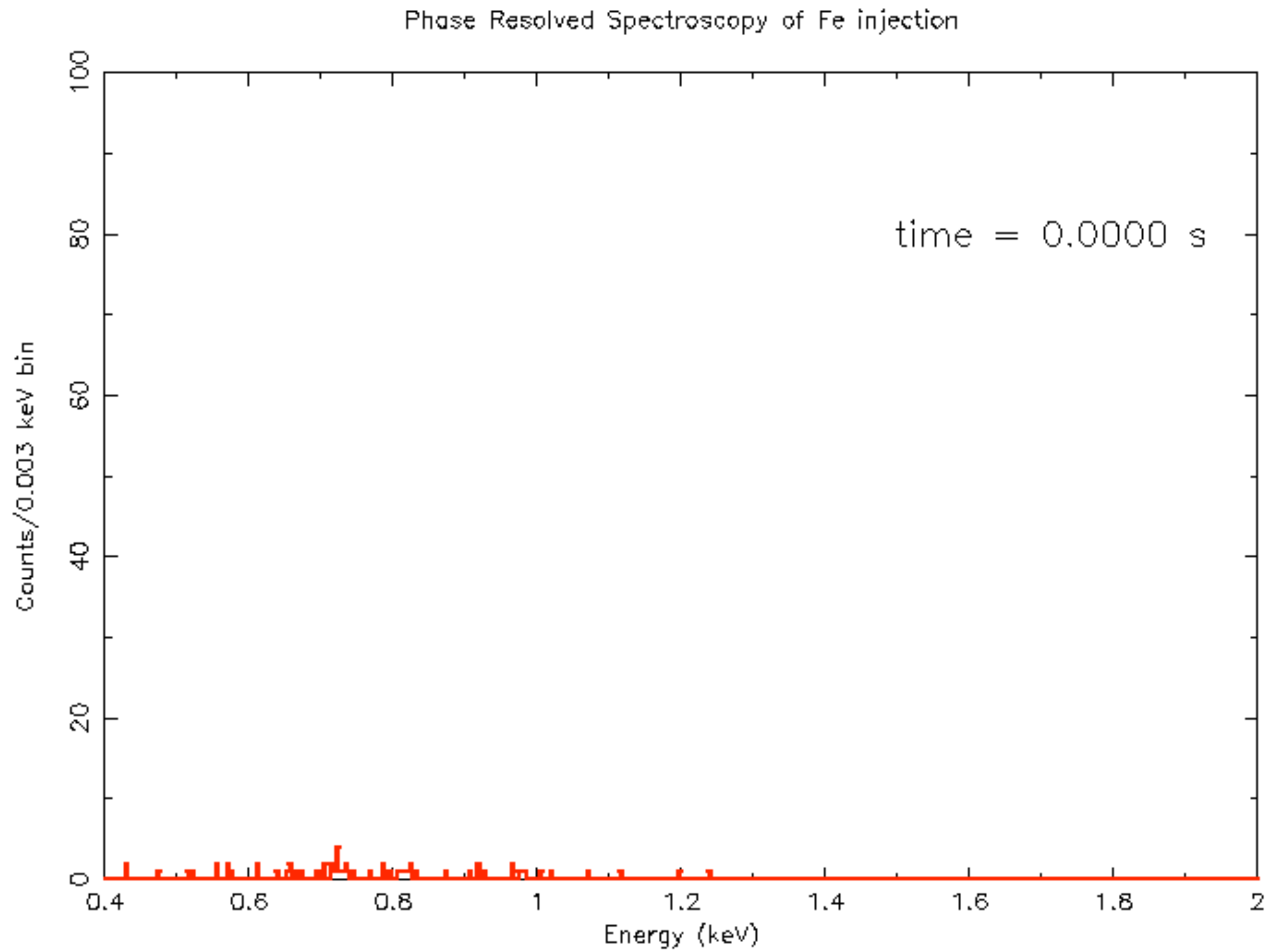

34 μm x 34 μm absorber
FWHM: 2.13 ± 0.07 eV
Counts per 0.25 eV bin
800
600
400
200
0
5870
5880
5890
5900
5910
5920eV
Energy [eV]
Energy [keV]
5.905
5.900
5.895
5.890
5.885
12:00 AM
1/14/10
3:00 AM
6:00 AM
9:00 AM
Time

Possibility to detect higher energy photons:



Energy information from time in saturation




Phase Resolved Spectroscopy of Fe injection
time = 0.0000 s
Counts/0.003 keV bin
0
20
40
60
80
100
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Energy (keV)