THE XEUS FOCAL PLANE INSTRUMENTS

Cryogenic Imaging X-ray Spectrometer (NFI), Cooling, and X-ray polarimeter

Piet de Korte
On behalf of the XEUS Instrument Working Group

SRON
Netherlands Institute for Space Research

Netherlands Organisation for Scientific Research

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- Tadayuki Takahashi, JAXA, J — Hard X-ray Imager
- Dick Willingale, Leicester, UK — X-ray optics

XEUS FOCAL PLANE INSTRUMENTS

Instrument		Mass (kg)	Power (W)
WFI	Wide Field Imager Si-based DEPFET array (excl. baffle)	90	254
NFI	Narrow Field Imager TES-based micro-calorimeter array (incl. cryostat + last cooler stage)	151	288
HXI	Hard X-ray Imager CdTe-based imaging array (excl. baffle)	31	61
HTRS	High Time Resolution Spectrometer Si-drift detectors	31	108
XPOL	X-ray POLarimeter (XPOL) Gas proportional imager	15	44

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REQUIREMENTS from XEUS Science Requirements Document_v5.

- X-ray Optics
  - 5 m^2 at 1 keV and 2 m^2 at 7 keV
  - 5 arcsec spatial resolution
- Field of View (arcmin)
  - 7′ Ø (WFI); 1.7′ Ø (NFI); 5′ x 5′ (HXI)
- Energy Range (keV)
  - 0.2 – 7 (NFI); 0.1 – 15 (WFI); 1 – 15 (HTRS); 1 – 40 (HXI)
- Energy Resolution
  - 150 eV @ 6 keV (WFI); 2 eV for E < 2 keV, and 6 eV @ 6 keV (NFI); 1 keV @ 40 keV (HXI)
- Count rate
  - 8 10^3 c/s 1% pile-up (WFI); ?8 10^3? c/s 10% pile-up (NFI); 2 10^6 c/s 10% pile-up (HTRS)
- Polarimetry
  - 2% for 10 mCrab in 10 ks (XPOL); 2% for 2 mCrab in 100 ks (XPOL)

Mirror Driven Specifications

Long Focal Length gives Large Collection Area, but also Large detectors.

- **Angular Resolution**

  5 arc sec resolution (Requirement) = 848 µm

- **Field of View**

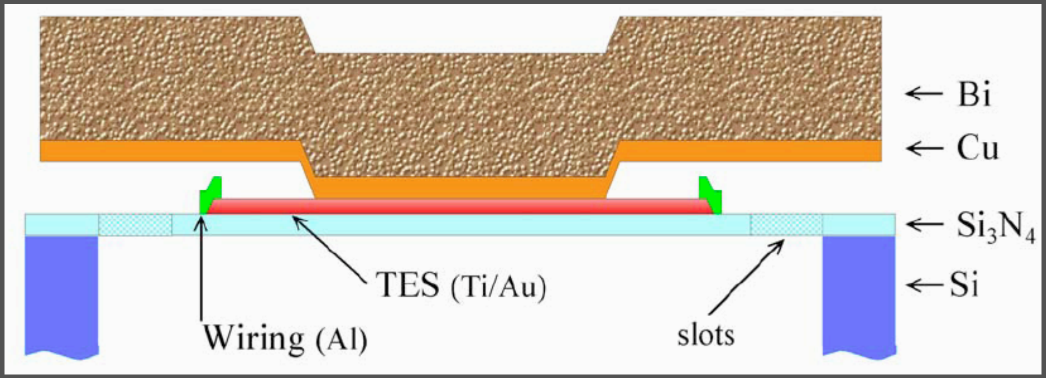
  7 arc min radius = 71 mm

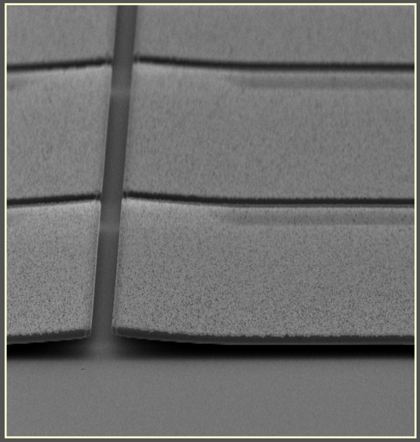
- **Large area**

  1mCrab ~ 300 c/sec

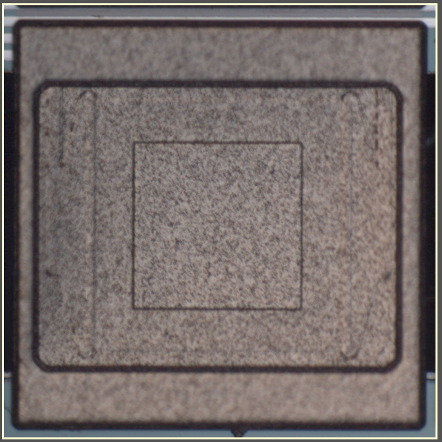
Narrow Field Imager - TES-based Micro-Calorimeter

PIXEL DESIGN



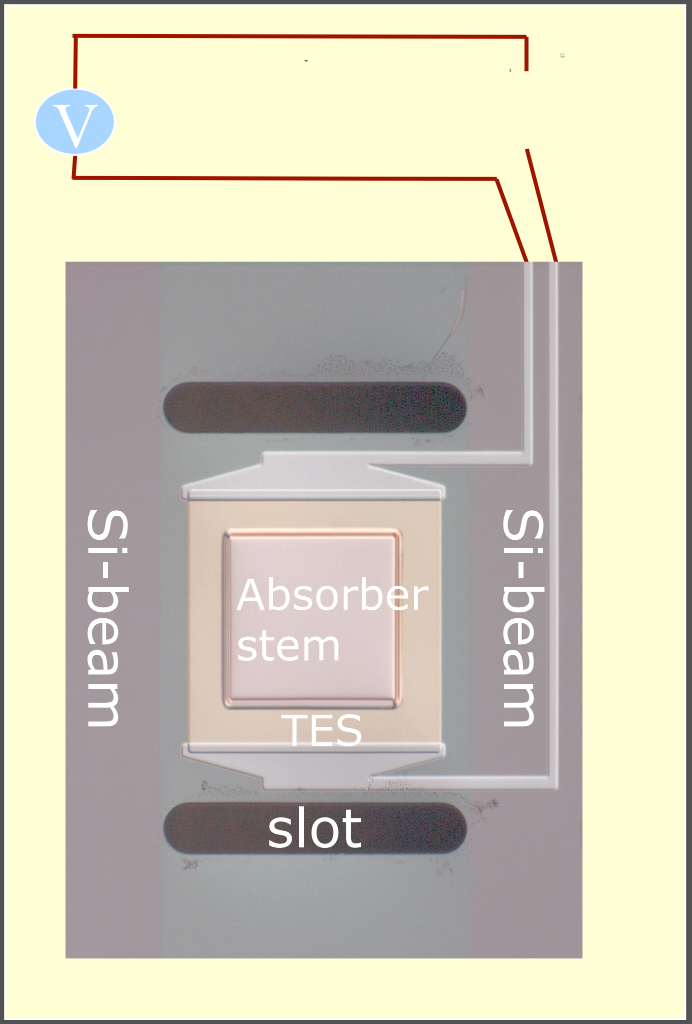


Side view



Top view

part of 5 x 5 array



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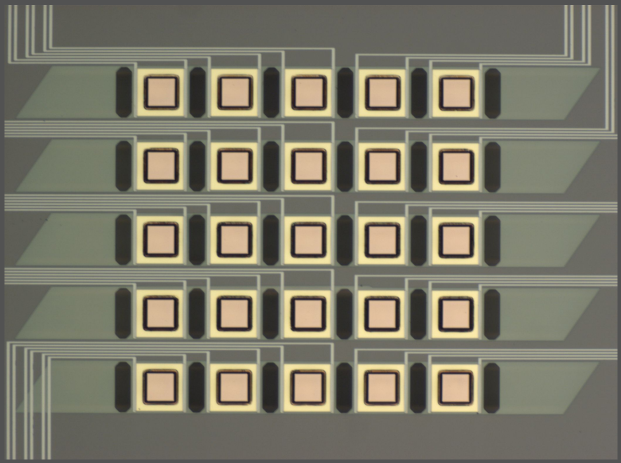
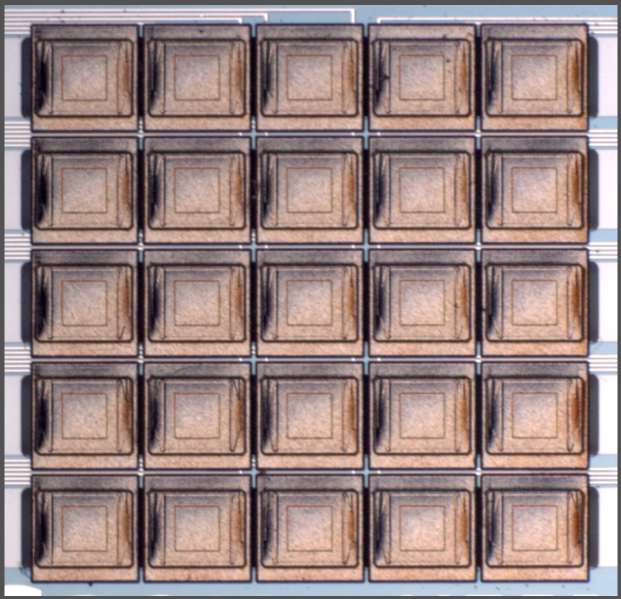
Narrow Field Imager - TES-based Micro-Calorimeter

ARRAYS



5 x 5 array

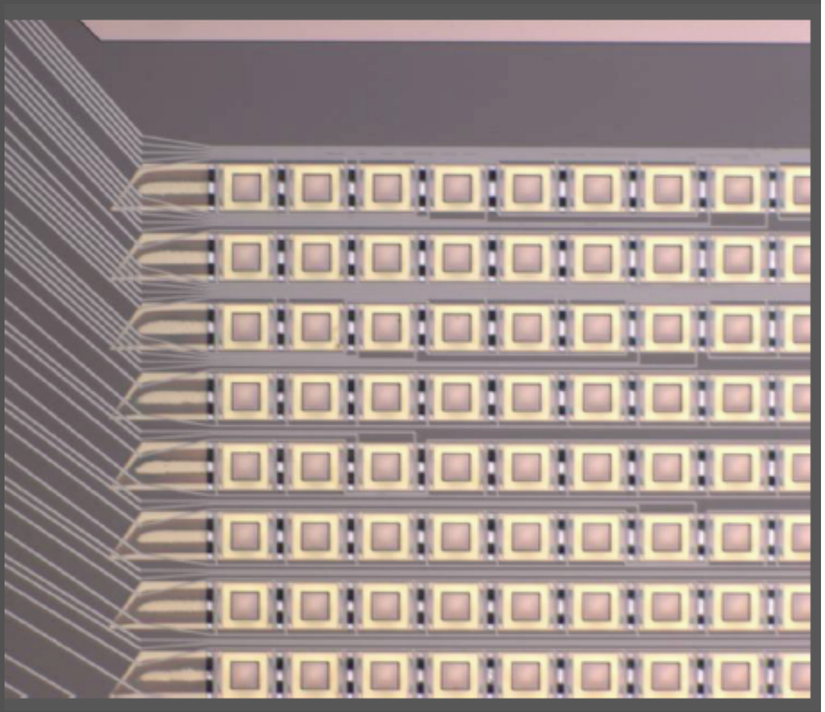
with Cu stems



5 x 5 array

with Cu/Bi

absorbers

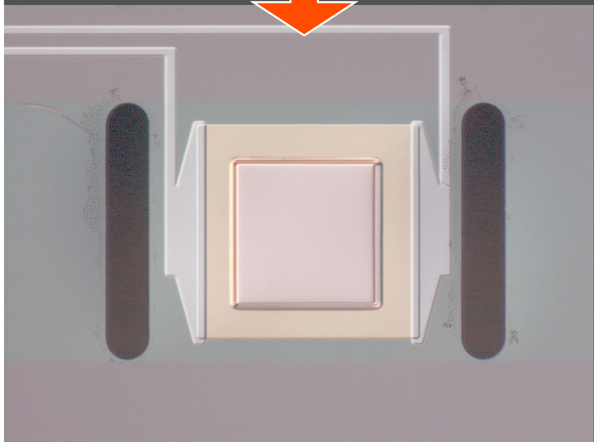


Close-up of 32 x 32 array

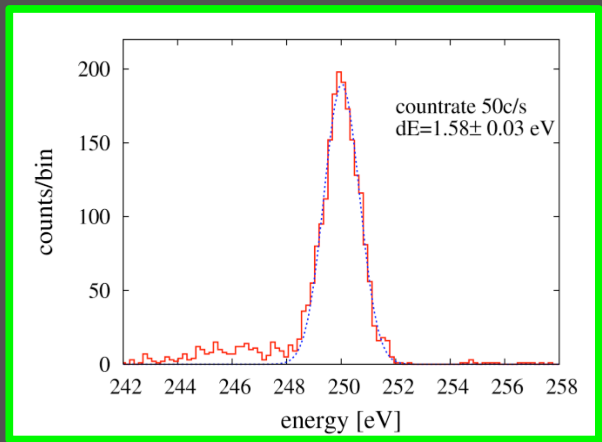
Narrow Field Imager - TES-based Micro-Calorimeter

PERFORMANCE for PIXELS from 5 x 5 arrays

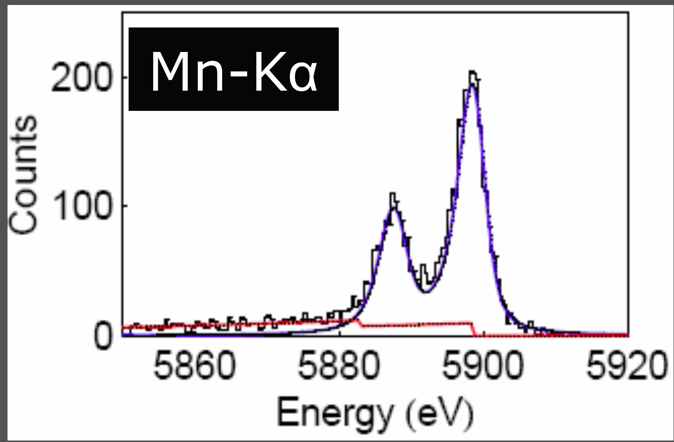
$\Delta E_{TDL} \approx 3.1$ eV



Cu-absorber



$\Delta E = 1.6$ eV @ 250eV

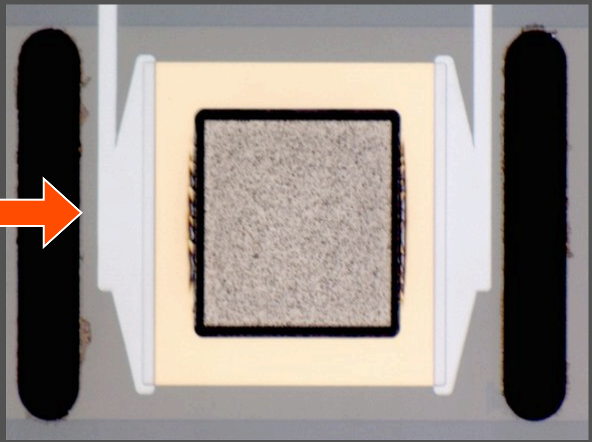


$\Delta E = 2.9$ eV at 5.9 keV

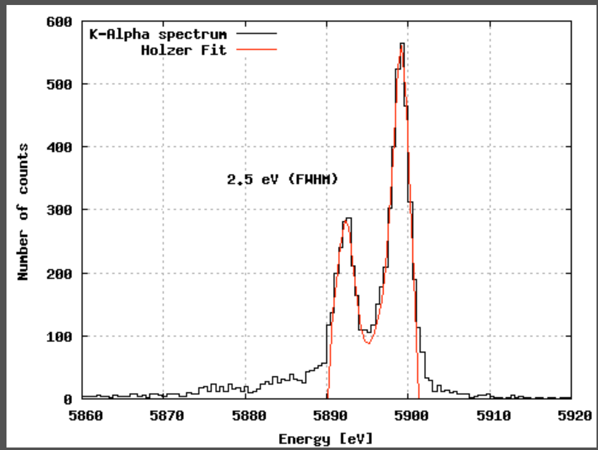
100 μs fall time

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

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



Cu/Bi-absorber



$\Delta E = 2.5$ eV @ 5.9 keV

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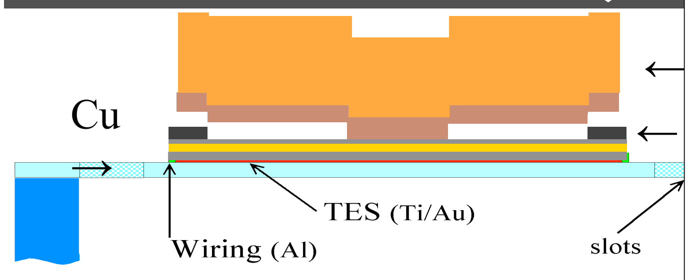
Narrow Field Imager - TES-based Micro-Calorimeter

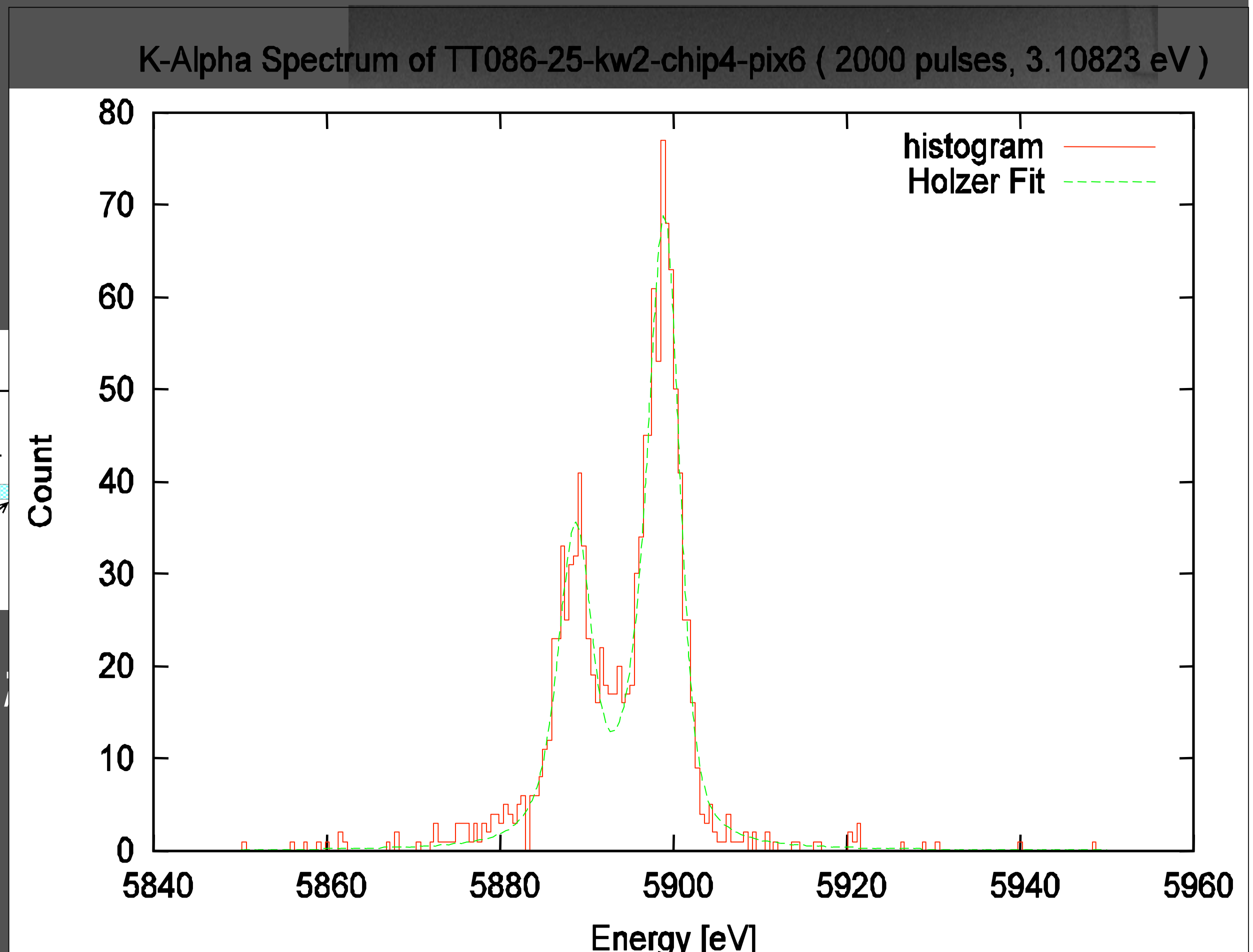
PERFORMANCE for PIXELS from 5 x 5 arrays

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

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



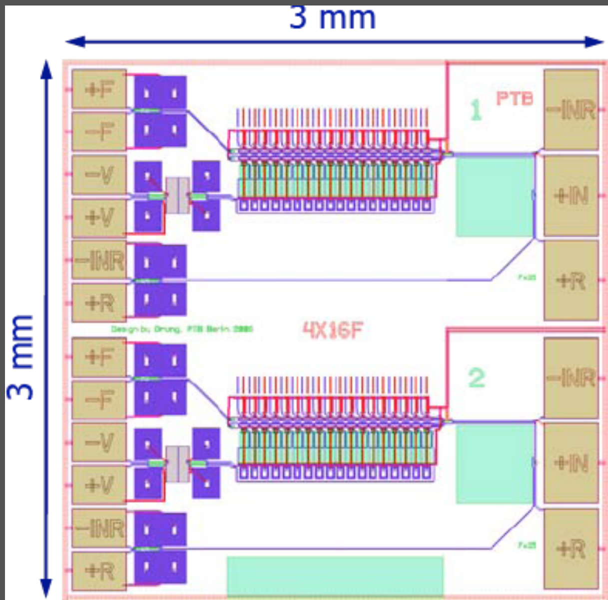
Cu/Bi-absorber (0.3/3 μm);
T_C = 116 mK



ΔE = 3.1 eV @ 5.9 keV

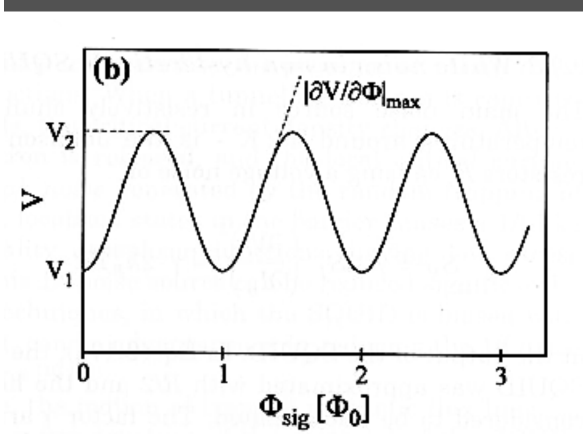
200 μs fall time

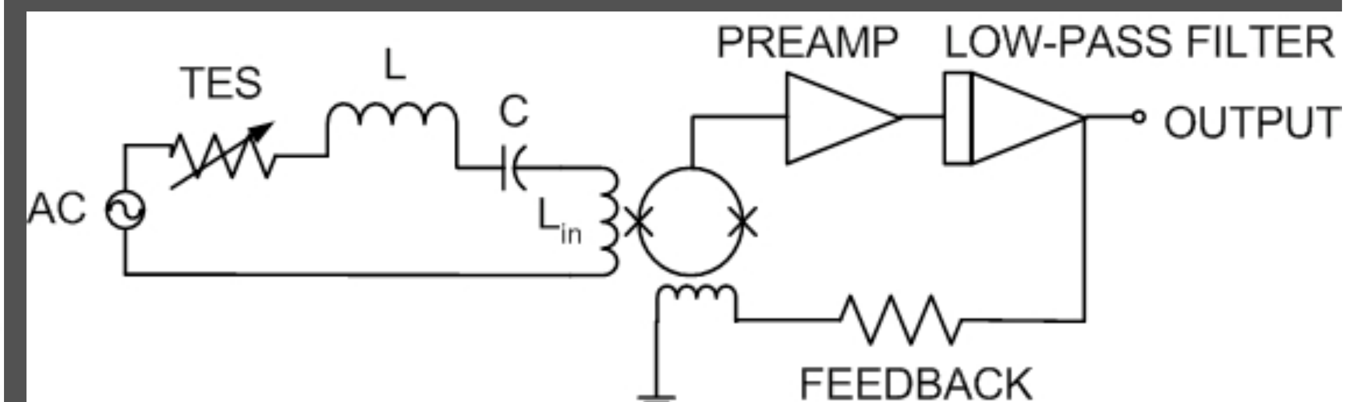
MICRO-CALORIMETER READ-OUT BY SQUID AMPLIFIER



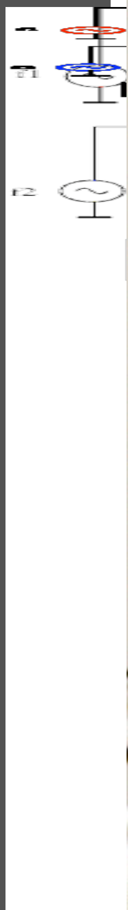
PTB 16-SQUID-arrays

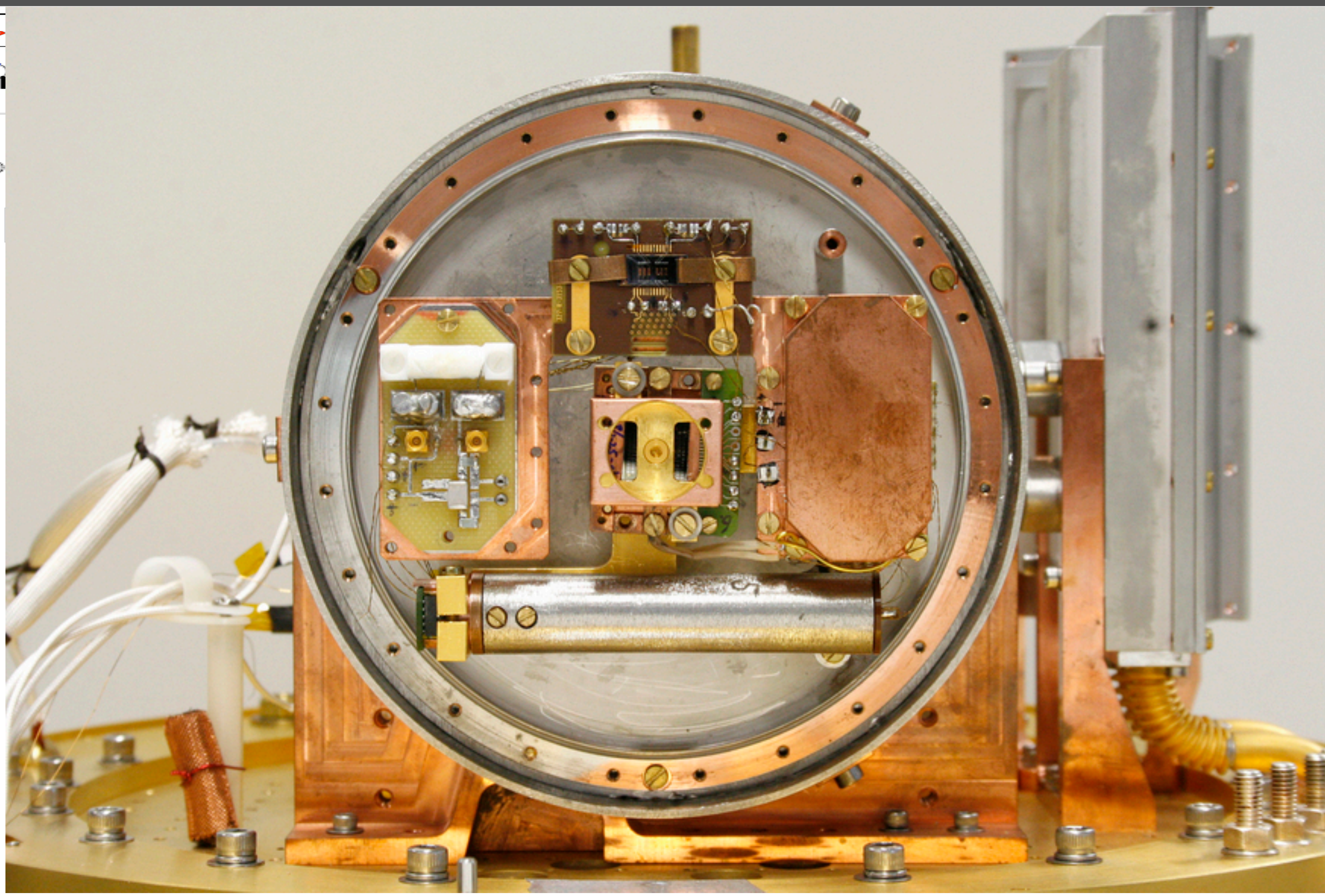
- Amplifier of magnetic flux. Works at < 4 K, P ~ 10 nW
- Current transferred to flux by SQUID input coil
- SQUID "Linear" dynamic range typically 5 10^5 √Hz
- Feedback with gain ~ 10 required for linearization and dynamic range improvement (flux-locked-loop/FLL)
- Standard FLL not enough gain-bandwidth → baseband feedback





FREQUENCY DOMAIN MULTIPLEXING
CURRENT SUMMING TOPOLOGY





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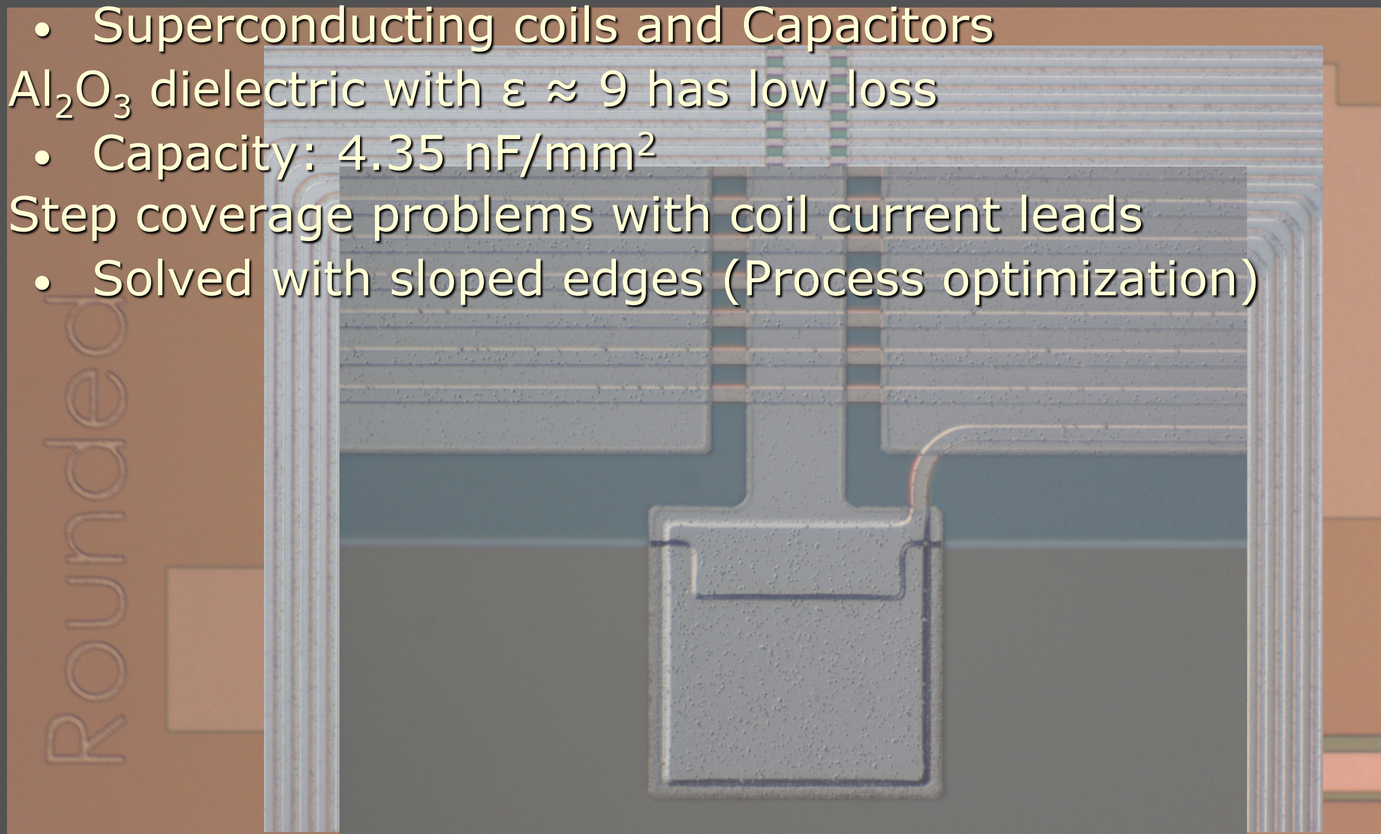
pixels/channel

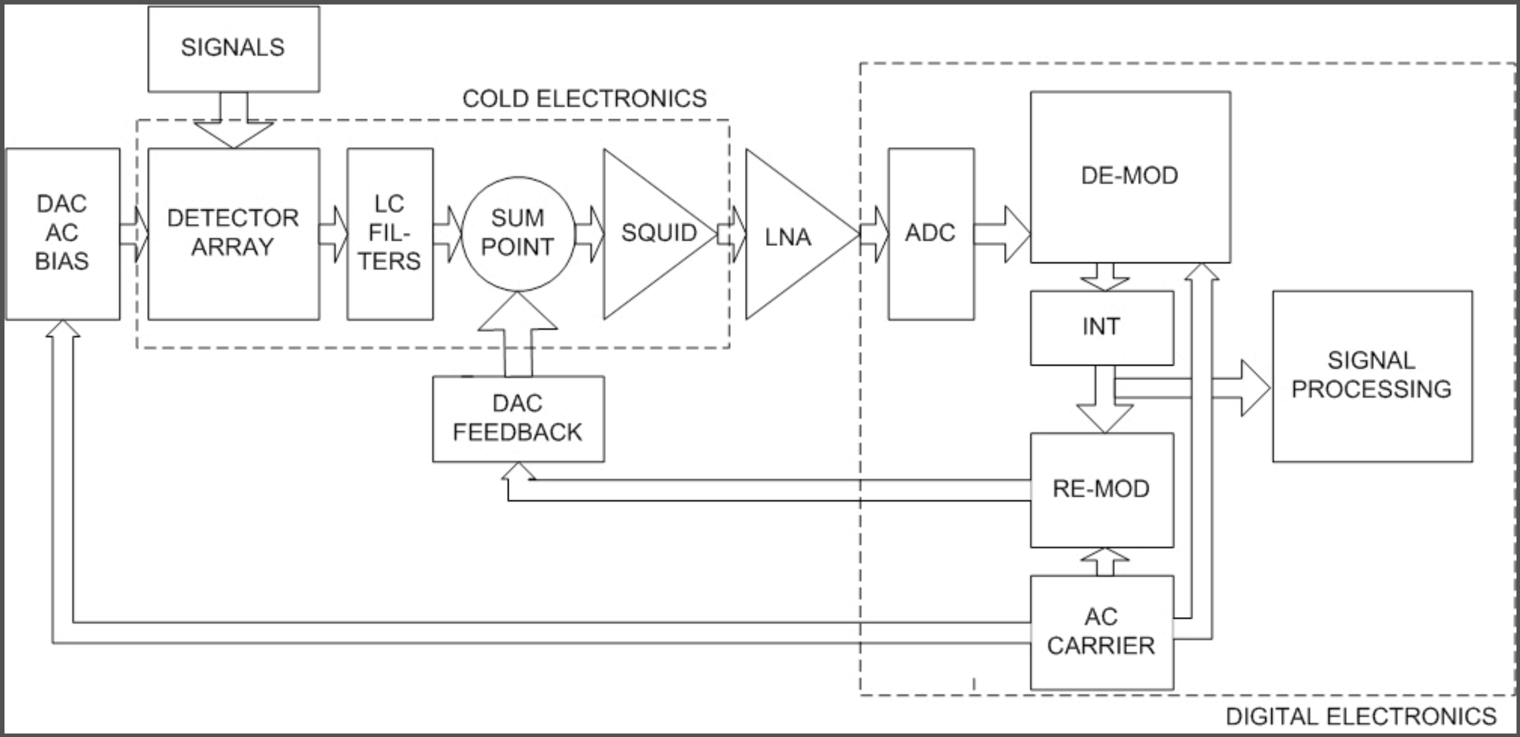
LC-filters

- Require high Q-factor, since $R_{LOSS} = \omega L/Q << R_{BIAS}$
  - Q > 800.f (MHz)
  - Superconducting coils and Capacitors
- Al_2O_3 dielectric with $\varepsilon \approx 9$ has low loss
  - Capacity: 4.35 nF/mm^2
- Step coverage problems with coil current leads
  - Solved with sloped edges (Process optimization)



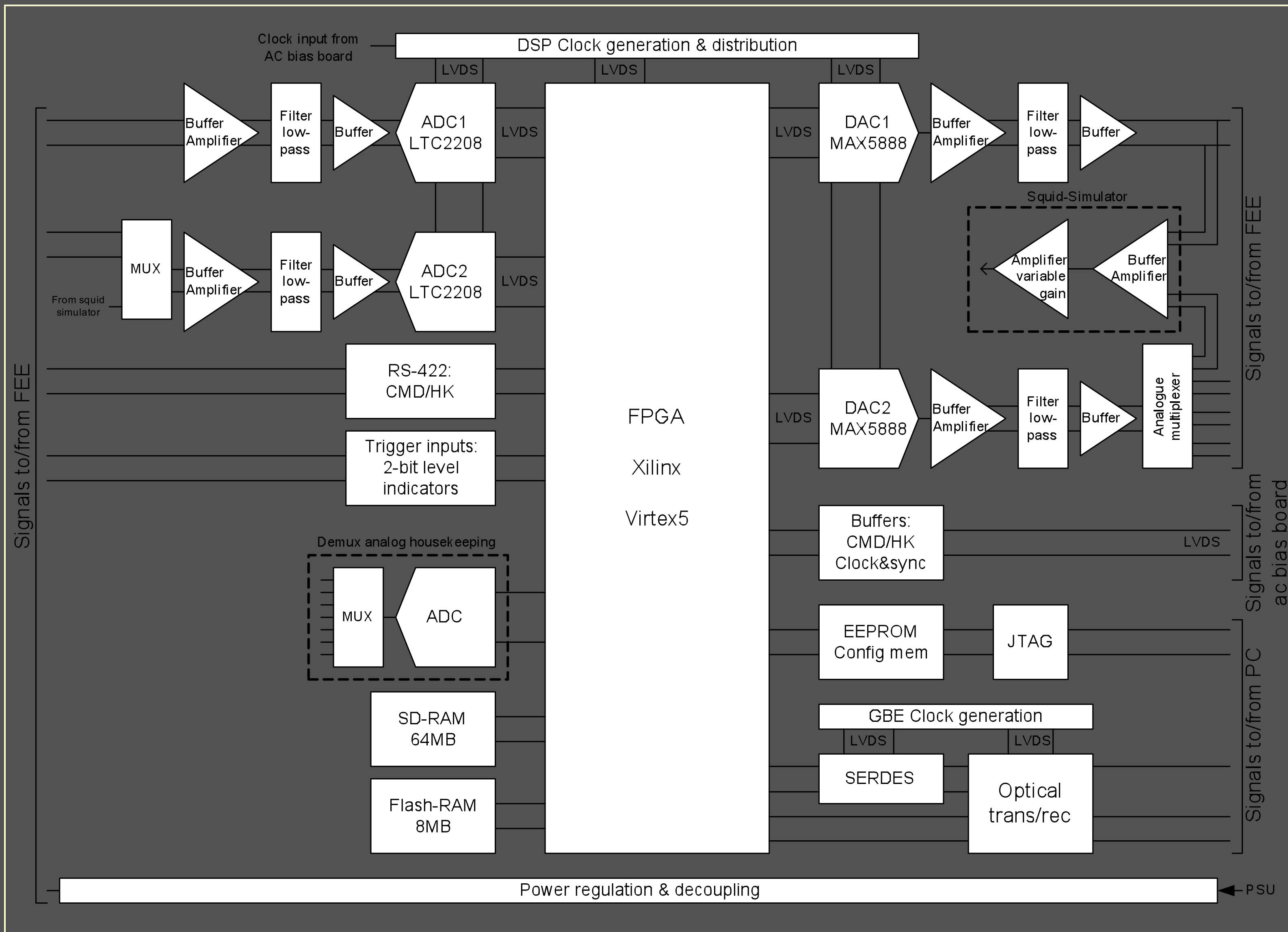
Q > 4000 measured and demonstrated

BASEBAND FEEDBACK

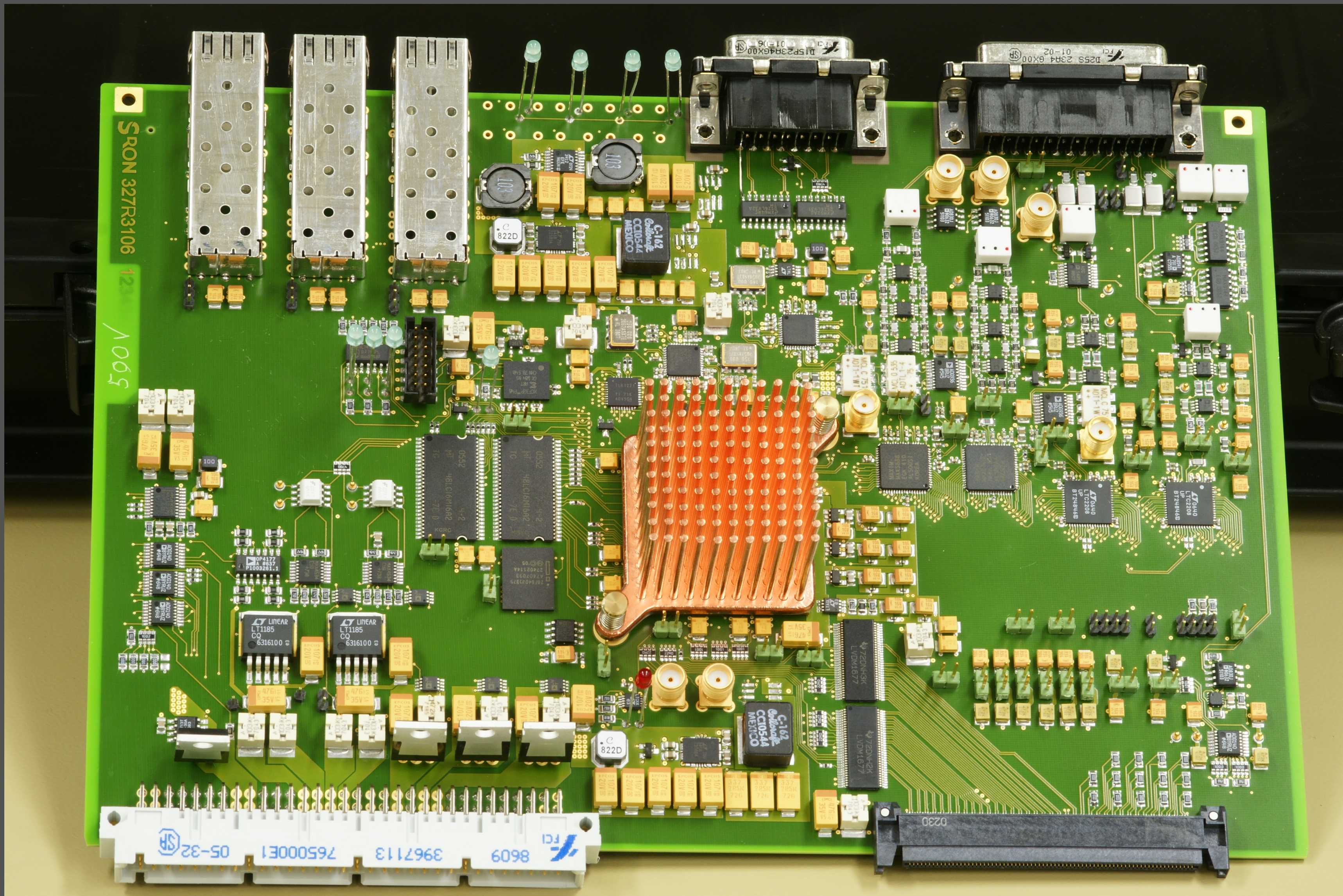


- Instability of feedback set by frequency separation of carriers (200 kHz) delay (250 ns) due to digitization and processing. Gain-bandwidth at base-band of about 30 kHz, so 3x feedback gain at highest signal frequency (10kHz)
- Performance tested on electrical breadboard.
- Bandwidth for carriers up to about 10 MHz (limited by SQUID back-action noise and LC-filter Q-factor)
- At least possible to multiplex 32 - 45 pixels XEUS type pixels

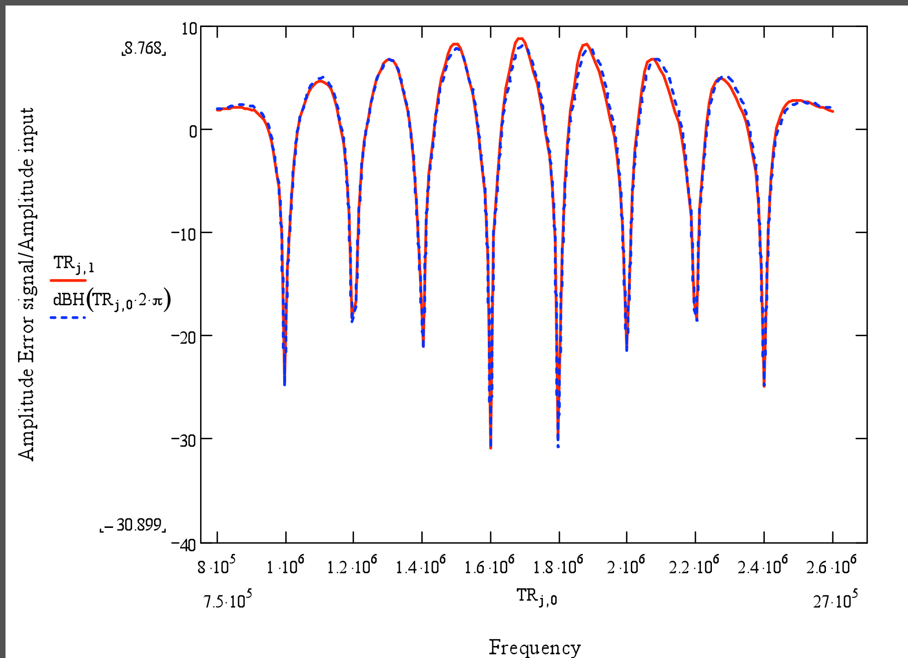
BaseBand Feedback Electronics board

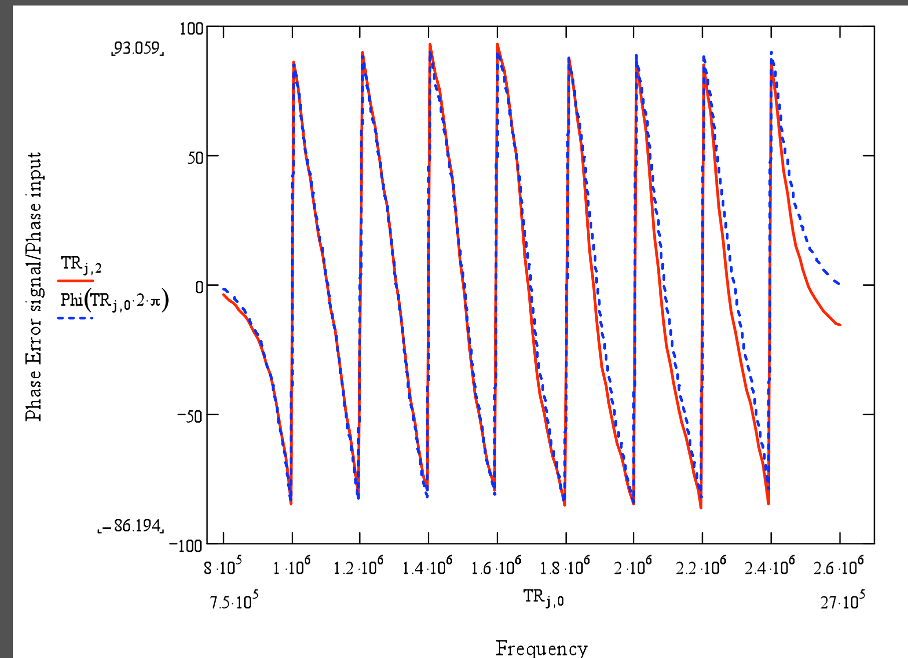


BBFB electronics board realization



Amplitude and Phase measurements/model of BBFB On a commercial Xilinx breadboard





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 3.5x at highest signal frequency (10 kHz)

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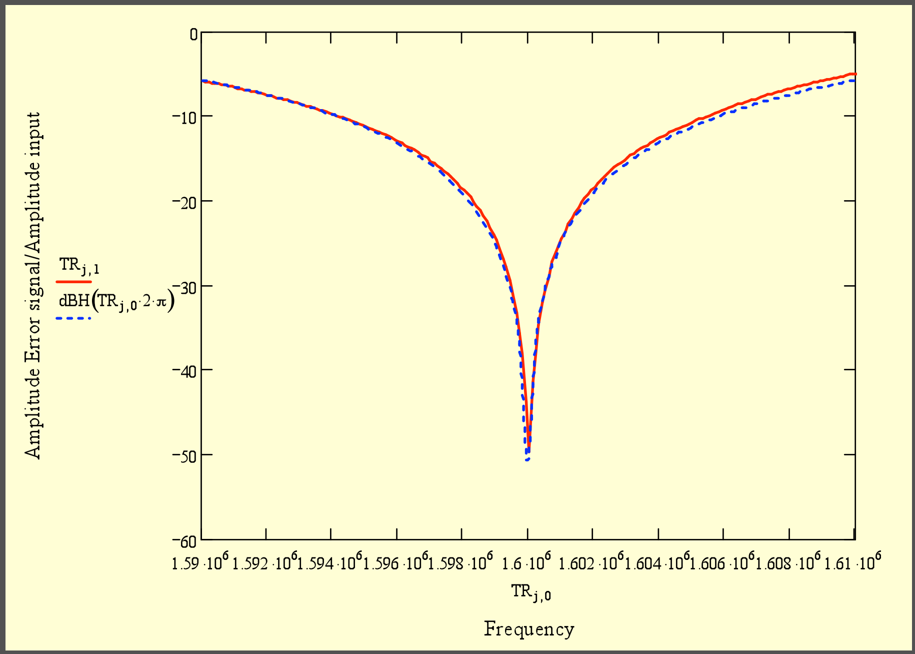
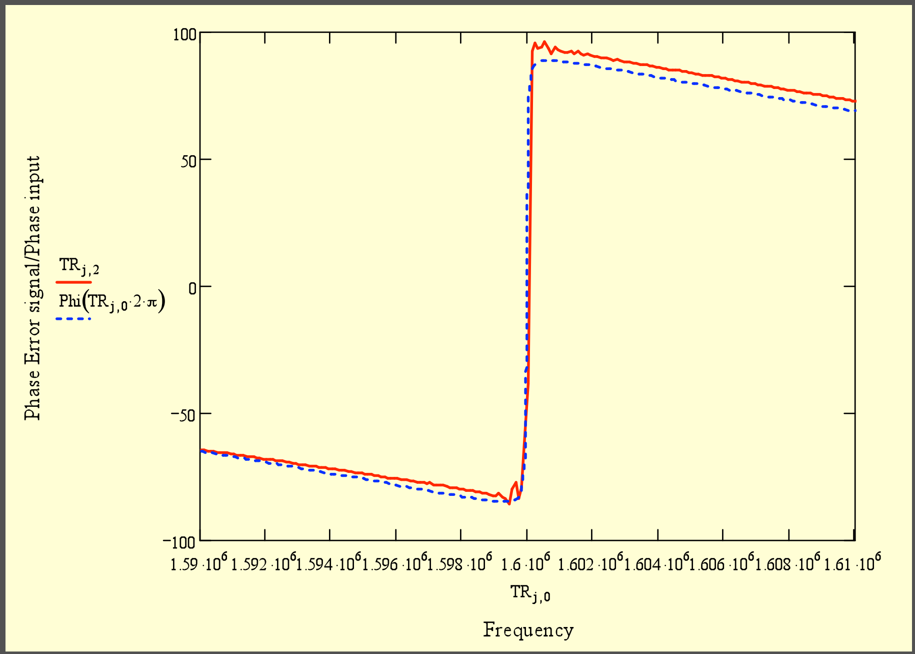
Amplitude and Phase measurements/model of BBFB On a commercial Xilinx breadboard





Measured carrier suppression – 50 dB for a gain-bandwidth of 18 kHz

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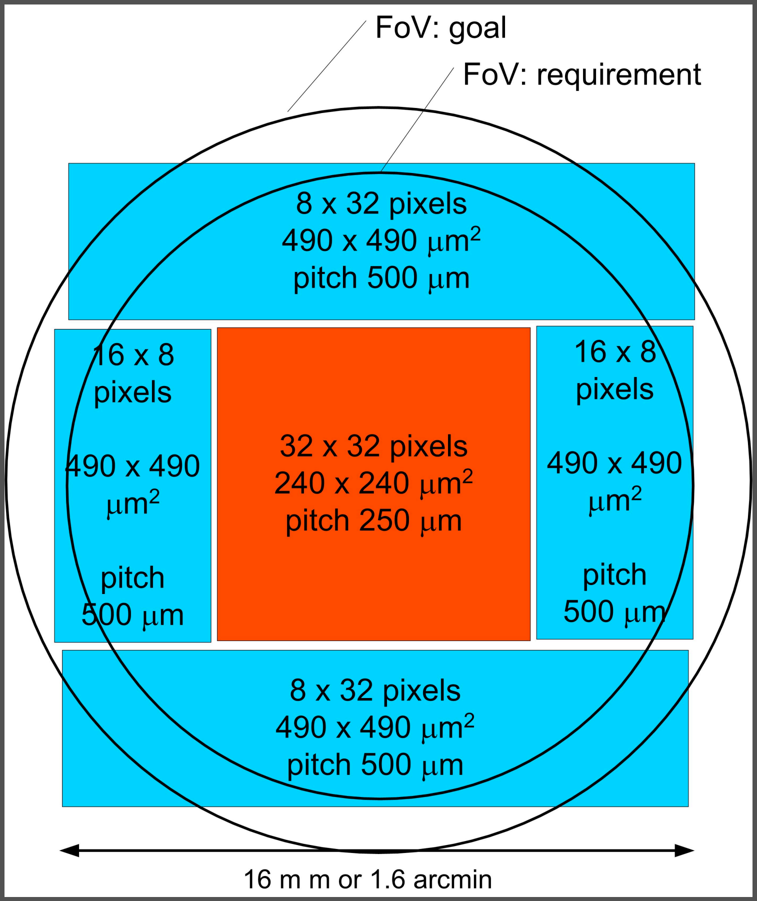
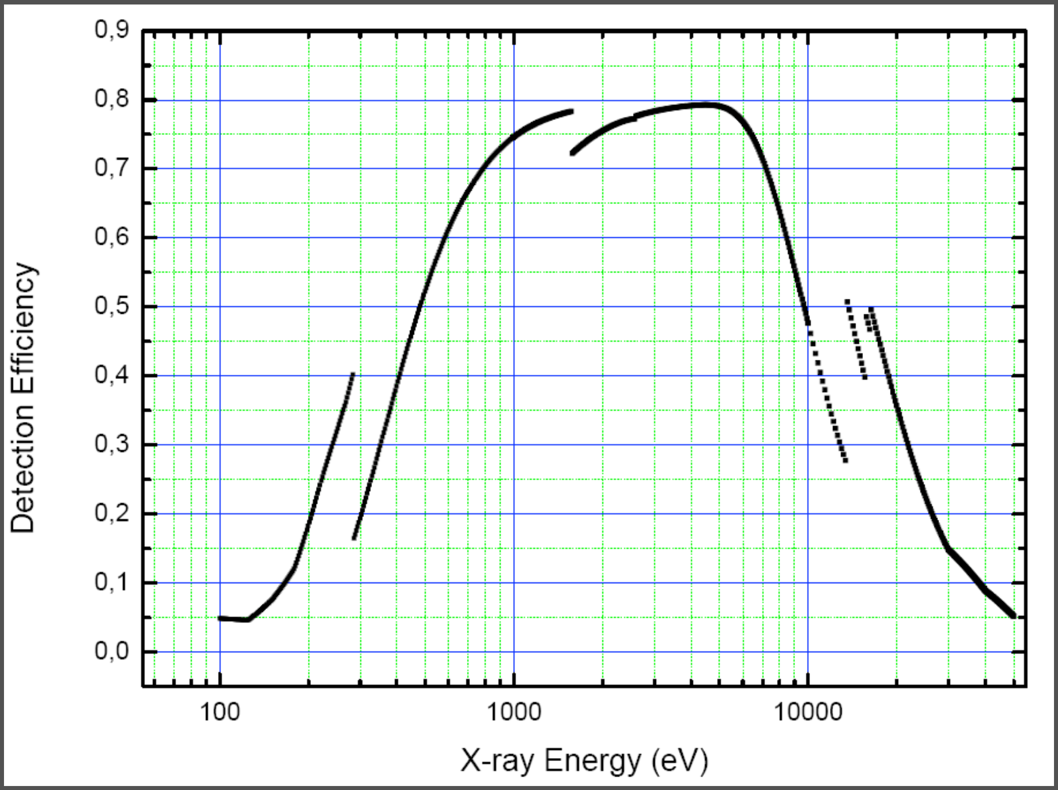
Narrow Field Imager - TES-based Micro-Calorimeter

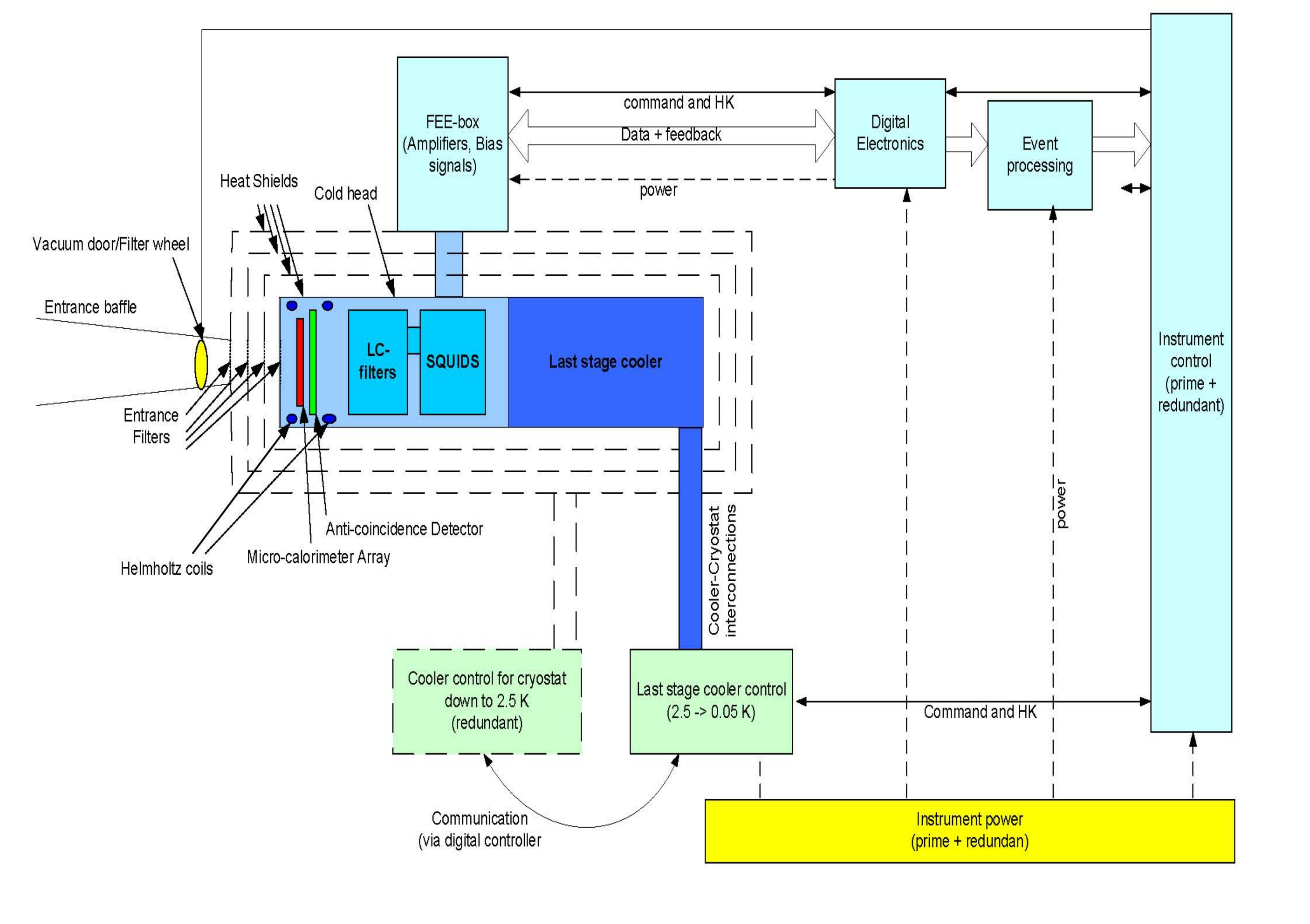


Field of View



Detection Efficiency (7 μm Bi)

Narrow Field Imager - TES-based Micro-Calorimeter



ΔE = 2 eV < 2 keV

1792 pixels for 1.7 arcmin diameter FoV

Energy 0.2 – 10 keV

Mass 151 kg (incl. last stage cooler)

Power 217 W

Requires 1 m long baffle

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TES micro-calorimeters in EUROPE
SRON and EURECA COLLABORATION

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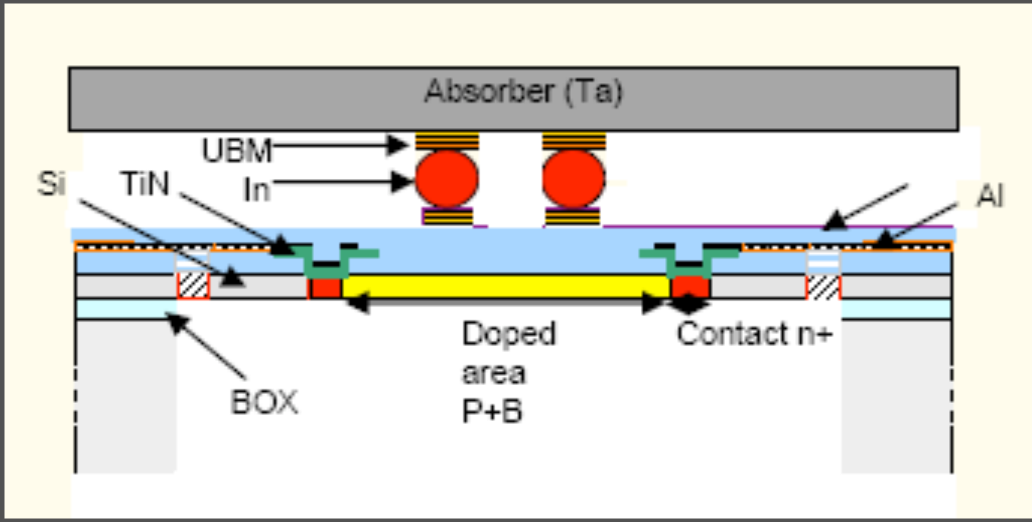
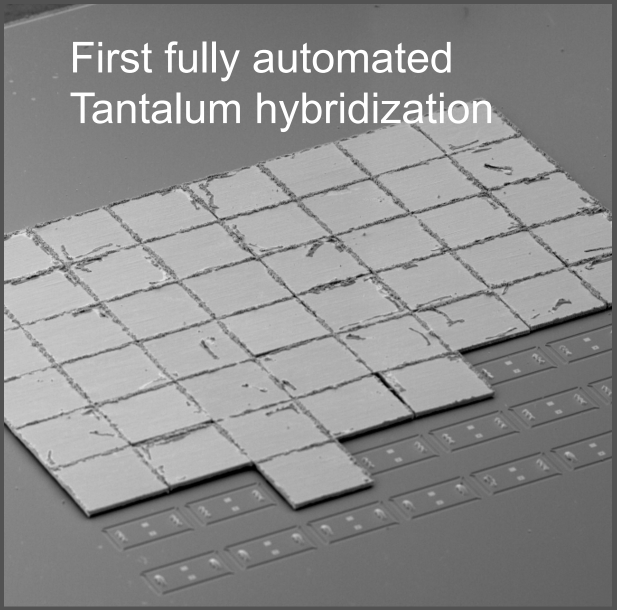
Si-doped X-ray Micro-calorimeter at CEA-Saclay

Herschel heritage: Developments by CEA-Saclay and LETI, Grenoble

Contributed paper by Claude Pigot

Fully integrated sensor with read-out multiplexer





Results: - Impedance of 8X8 sensor matrix in the right range with good sensitivity
- Integration of absorber matrix onto sensor matrix promising

Next steps: April 2008: First 8X8 array with freed Sensor & Absorber
End 2008: 1st Iteration Cold Electronics

Pro: Fully integrated system with multiplexed read-out

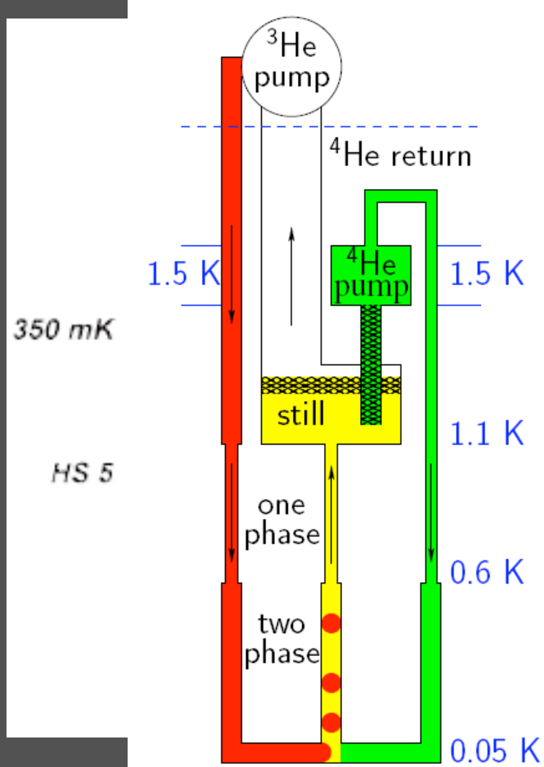
Con: Till now no X-ray performance data, use of Ta-absorbers by other teams failed, potentially slow response, developments late for XEUS.

Narrow Field Imager - TES-based Micro-Calorimeter

Interface with satellite cryostat at 2.5 K with 10 mW cooling power

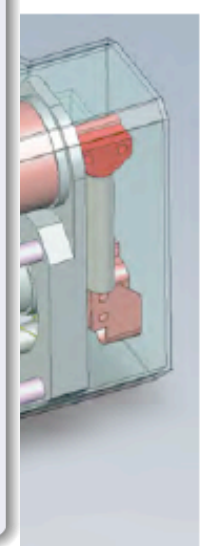
Options under development:

Closed cycle ... (Institut Neel)
He3 sorption/1stage ADR (CEA Grenoble)
2 stage ADR (Astrium/MSSL/JAXA)
30 W and 31 kg for 1 μW during 30 hours
25 W and 5 kg for 1 μW during 30 hours

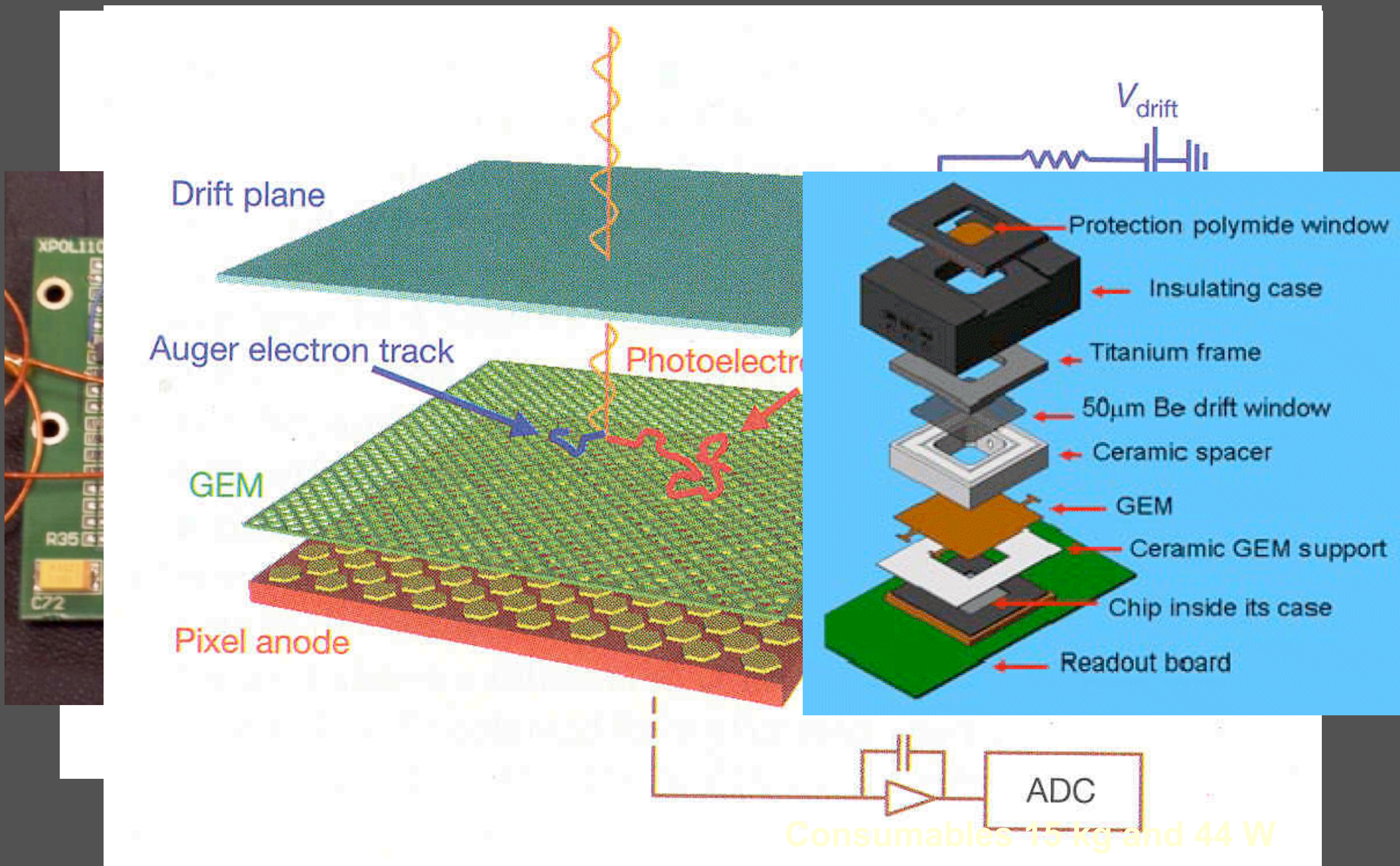


XEUS - NFI X-ray experiment

- requires 1 μW at 50 mK for ADR
  - CCDR meets requirement with $\dot{n}_3 = 30\ \mu$mole/s, $\dot{n}_4 = 120\ \mu$mole/s and a heat exchanger of $L = 9$ m and $d = 0.4$ mm
  - better thermalization of wiring reduces required cooling power for CCDR
- precooling stage of XEUS delivers 10 mW at 2.5 K
  - CCDR needs 5 mW at 1.5-1.8(?) K
  - solution: ^{3}He Joule-Thompson expansion from 15 K or with SPICA technology



X-ray Polarimeter



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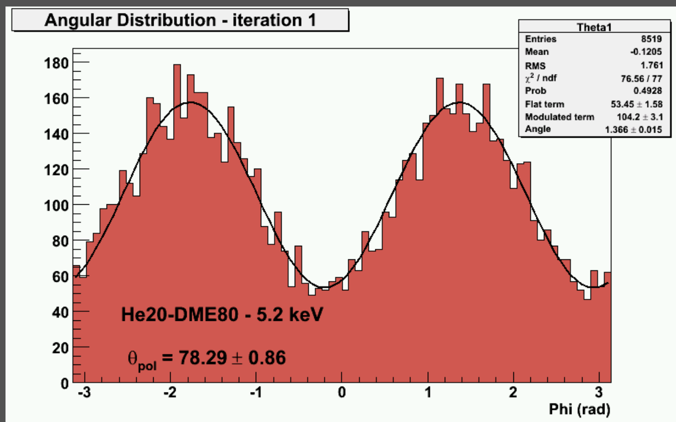
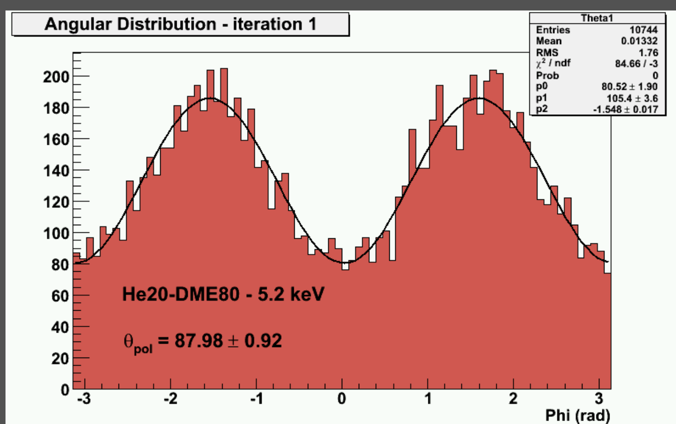
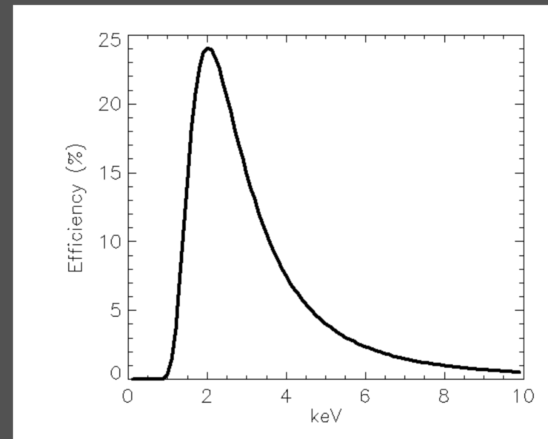
XPOL - Performance

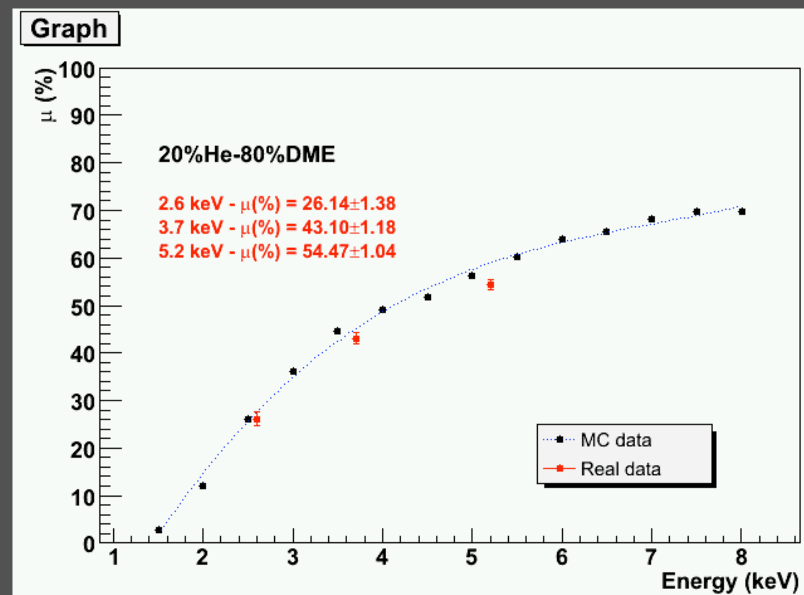




5.2 keV polarized photons for two angular rotations of the polarizer showing the good angular sensitivity.



Detection-Efficiency



The modulation factor measured at 2.6 keV, 3.7 keV and 5.2 keV compared with the Monte Carlo previsions.