

# LEAPS-INNOV germanium for X-ray spectroscopy (Detector integration & test)

Paco Iguaz\* - on behalf of WP2 of LEAPS-INNOV  
RSC, ICJLab, Orsay (France), 12<sup>th</sup> June 2026

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*This project has received funding from the European Union's Horizon 2020  
research and innovation programme under grant agreement No. 101004728*

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- **Frascati:** A. Balerna
- **Jagiellonian Univ.:** T. Kolodziej
- **MAX-IV:** P. Bell, M. Cascella, K. Klementiev, D. Ward
- **PSI:** B. Schmitt
- **SOLEIL:** Nishu Goyal<sup>2</sup>, F.J. Iguaz, C. Menneglier
- **XFEL:** S. Aplin, M. Porro, M. Turcato

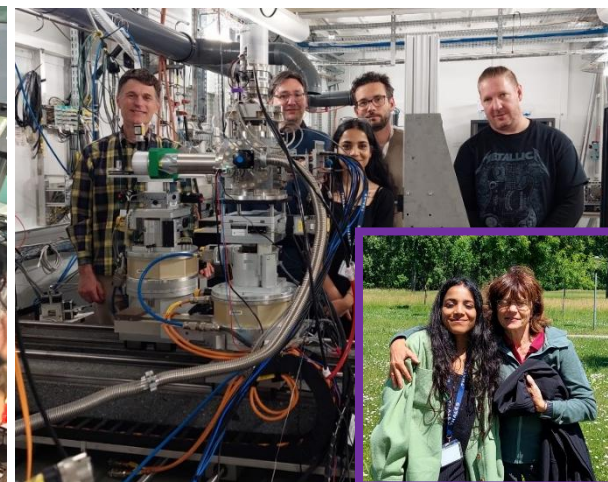
(1) Also at INFN Trieste and Mid Sweden Univ.

(2) Now at XFEL

+ **XGLab S.r.l.** + **ESRF/SOLEIL facilities**



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- Scientific motivation
  - EDX detectors
  - Motivation for germanium detectors
- LEAPS-INNOV germanium detector
  - Project description
  - Highlights: sensors, electronics, mechanics
  - Detector integration
  - Performance of first prototype
- On going actions

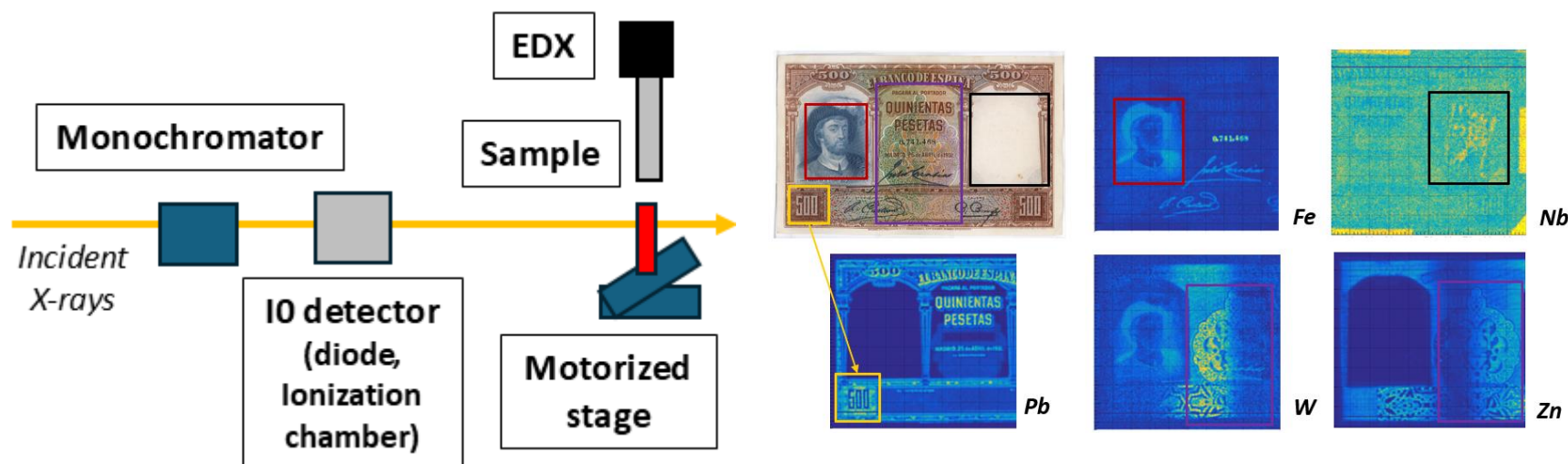
**Bibliography:**

- 1) N. Goyal *et al.*, submitted to NIMA, arXiv:2504.16482
- 2) N. Goyal *et al.*, NIMA 1081 (2026) 170835
- 3) M. Quispe *et al.*, JaCoW IPAC2024 (2024) TUPR75
- 4) E.N. Gimenez *et al.*, JPCS 3010 (2025) 012144
- 5) F. Orsini *et al.*, NIMA 1045 (2022) 167600

P. Rehak *et al.*, *Nucl. Intr. Meth. A* **624** (2010) 260-264

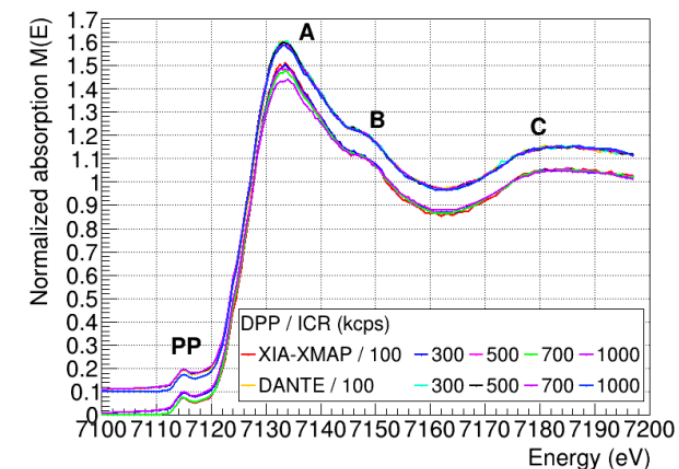
D.M. Schlosser *et al.*, *Nucl. Intr. Meth. A* **624** (2010) 270-276

- Counting detectors resolved in energy
- Linear counting rate between  $10^3$  and  $10^6$  cps
- Types: **Silicon Drift Detectors (SDD)**, multi-element germanium (**HPGe**), **CdTe**
  - # elements: 1-36. Active surface: 10 to 100 mm<sup>2</sup> (collimated)
  - Individual sensors or monolithic sensors (back-side pixelated)
- Applications: **XRF/XAS**



*Experimental setup*

*X-ray Fluorescence (XRF)*



**X-ray Absorption Spectroscopy (XAS)**

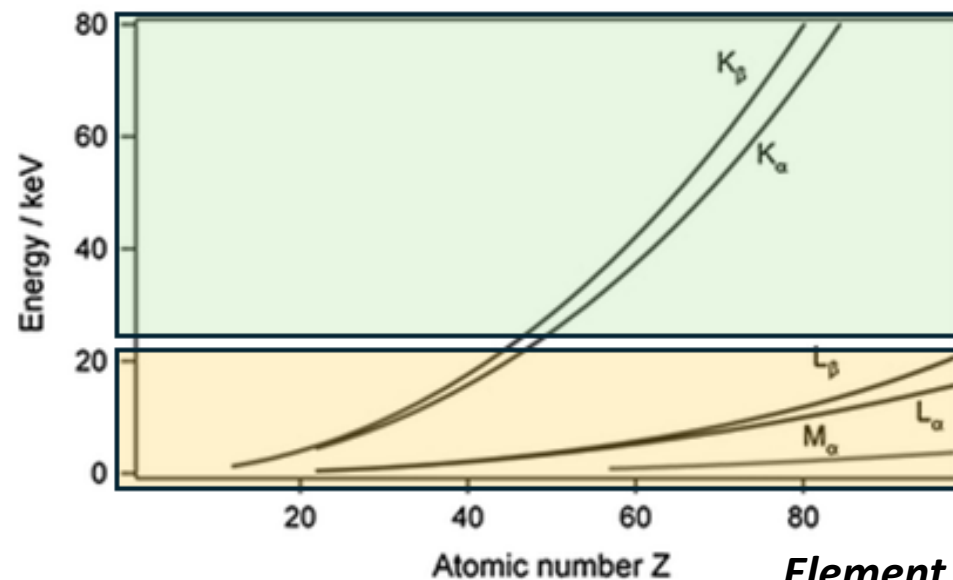
## Why Germanium ?

E > 20 keV: energy dispersive technology cannot be Si-based

(limit effect increasing thickness from 0.5 to 1 or 2 mm)

	Silicon	Germanium
Z	14	32 <b>Greater absorption</b>
Density (g/cm <sup>3</sup> )	2.33	5.32
Ionization energy (eV)	3.74	2.96 <b>Better resolution</b>
Band gap (eV)	1.1 Operation at -42°C	0.67 • Operation at 77°K • IR screen
h <sup>+</sup> /e <sup>-</sup> mobility (cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> )	500/1500	2000/4000 <b>Faster collection</b>
Capacitance	< 1 pF (SDD)	1-10 pF <b>Higher capacitance (GDD not yet available)</b>

Detector range



Element  
(Physics case)

	Soft/Tender X-rays (< 20 keV)		Hard X-rays (20-100 keV)	
	ε	S/B	ε	S/B
SDD	100%	2 × 10 <sup>4</sup>	30% (20keV), 10% (30 keV)	< 0.5 × 10 <sup>4</sup>
HPGe	100%	0.3 × 10 <sup>4</sup>	85-90%	0.5-1.0 × 10 <sup>4</sup>

## LEAPS-INNOV germanium project

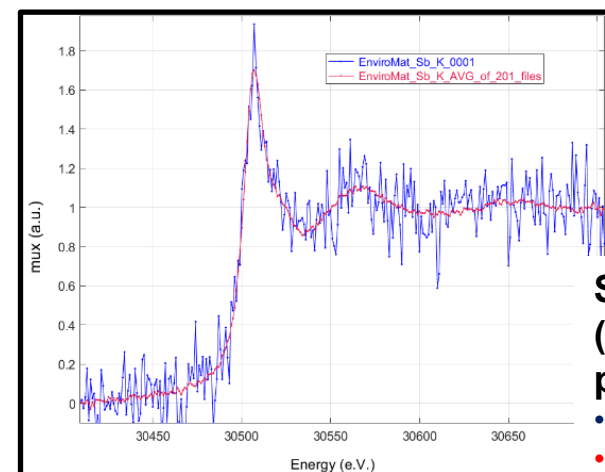
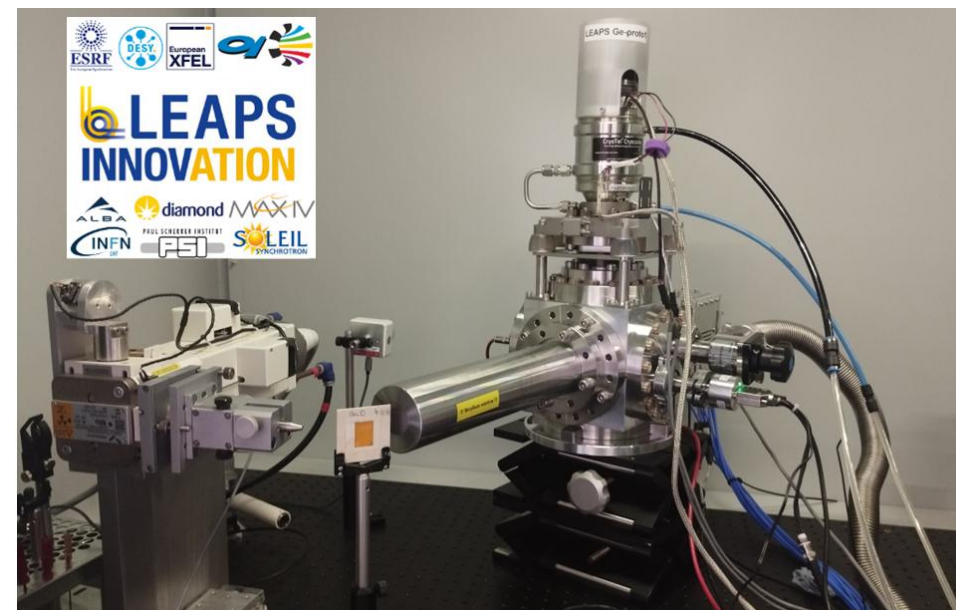
- New multi-element monolithic germanium detectors for XRF/XAS
- Project funded by HORIZON 2020: May 2021 – Sep 2025
- **Collaboration:** DLS (sensors), SOLEIL (electronics), ALBA (thermal), DESY (mechanics), ESRF (integration)
- **WP2 coordinators:** E.N. Gimenez (DLS) & F.J. Iguaz (SOLEIL)
- **Production plan** prepared for knowledge transfer to industry

## Motivations

- Overcome the **limits of current commercial detectors**
- Open new possibilities of experimentation in a **large energy range [5-100 keV]** with **higher throughput capability**
  - Advance material, energy, environmental science, cultural heritage

## Technological building blocks

1. Germanium sensor (4 mm thick, 5 & 20 mm<sup>2</sup> pixel size)
2. Full electronics chain (TETRA ASIC, FEB, BEB)
3. Cooling and mechanics system



**Scientific case**  
(Sb 5.5 ppm traces in polluted soil)

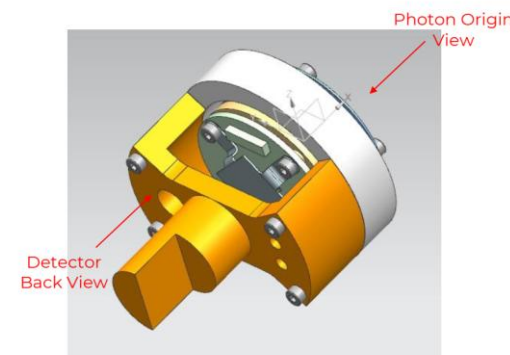
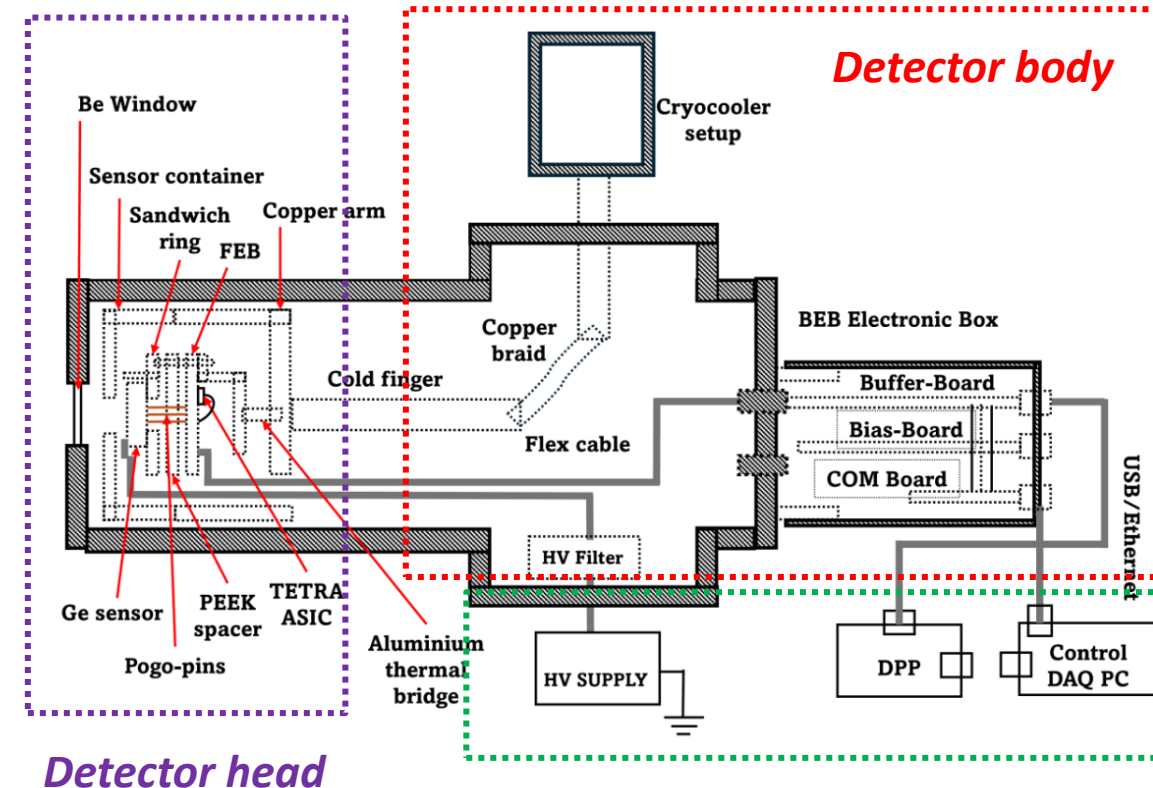
- **Blue line:** 1 run (95 sec)
- **Red line:** 200 runs (> 5h)

## Detector specifications:

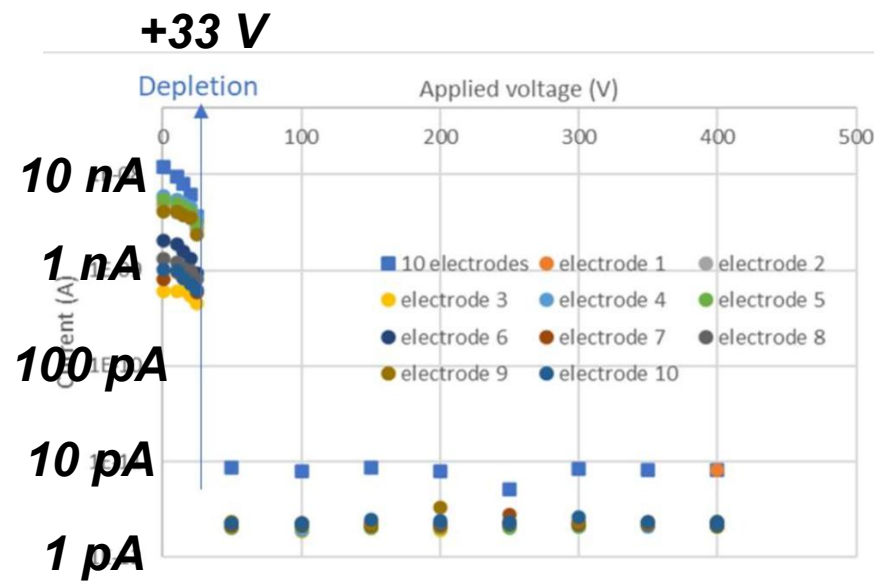
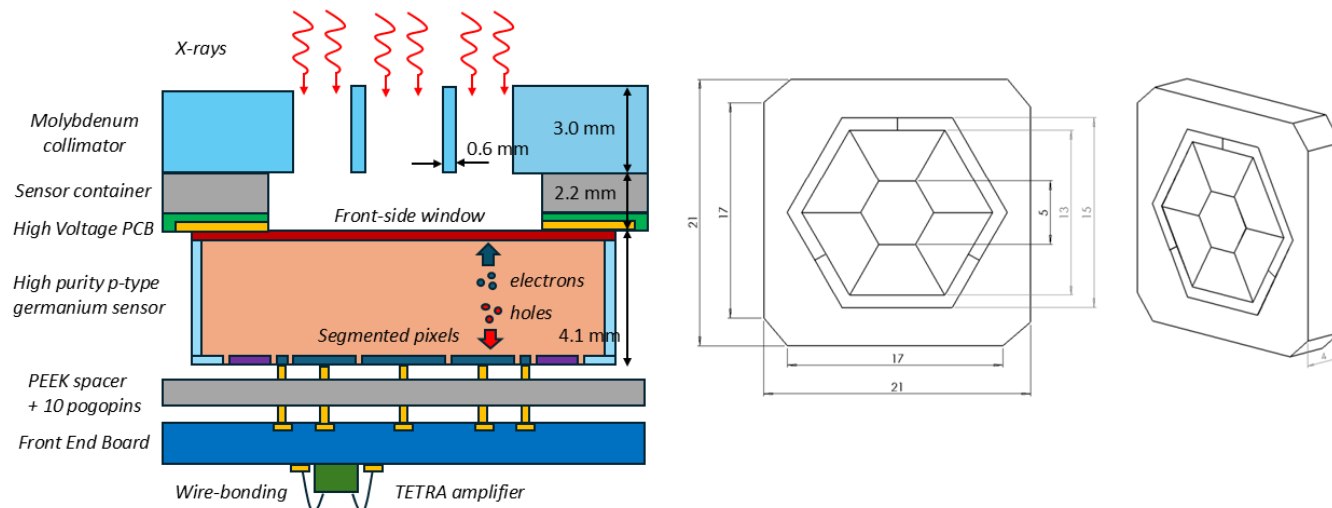
- **Mechanics:**
  - Nose dimensions: **300 mm length,  $\varnothing$  67 mm**
  - Operation at **77°K**
- **Performance:**
  - Energy range: **5-100 keV**
  - Energy resolution: **180 eV at 5.9 keV (PT of 1 us)**
  - Dead time: **<30% at 1 Mcps**
  - Peak-to-background: **>1000**
  - Pixel cross-talk: **< 0.2%**

## Main parts:

- **Detector head:** germanium sensor, front-end electronics & interconnection
- **Detector body:** Cooling system, cryostat with its flanges, back-end electronics with its housing
- **Ancillary systems:** digital pulse processor, voltage power supplies & equipment for control & monitoring



- Multi-element high-purity germanium sensors manufactured by Mirion Technologies
  - Hole collection mode, p-type Ge bulk
  - 1 central hexagonal pixel, one ring with six (6) trapezoidal pixels, 3 ancillary ring-shaped pixels
  - Thick: 4 mm. Pixels: 20 mm<sup>2</sup>
  - Depletion voltage: +33 V
  - Operation voltage: +75 V to +300 V
  - Leakage current: < 1 pA at 77°K
- Interconnection between germanium sensor & FEB pads is made by *pogo pin connectors*
  - Dimensions: 6.9 mm long, Ø 0.2 mm tips
  - A *PEEK spacer* keeps the pogo pins in place
  - Indium foil was also introduced



E.N. Gimenez et al., J. Phys. Conf. Ser 3010 (2025) 012144

- **TETRA ASIC:**

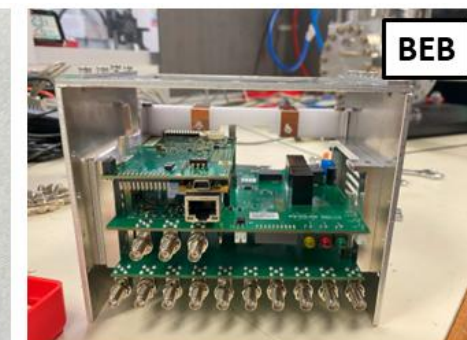
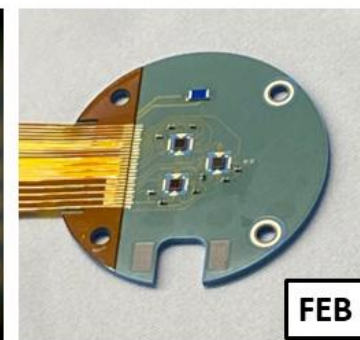
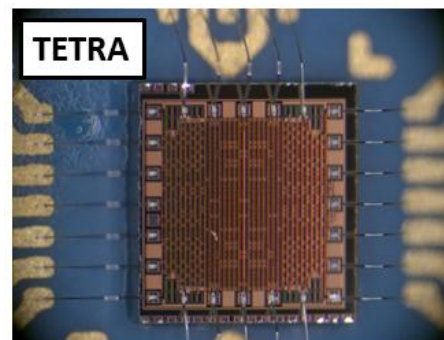
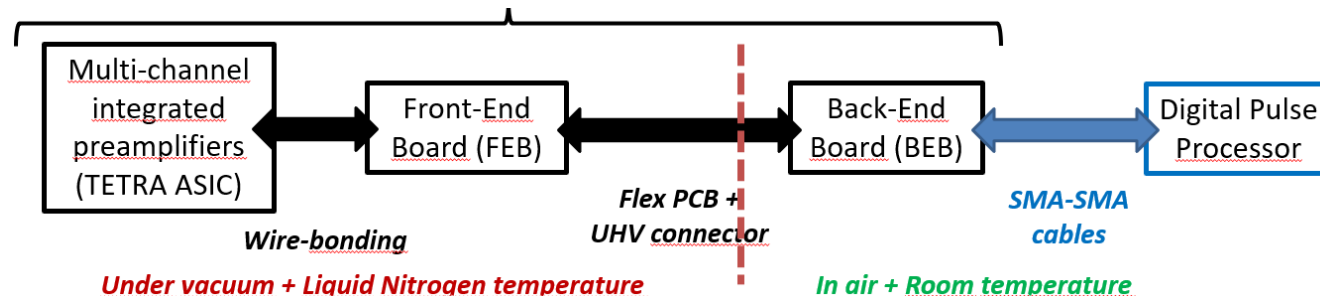
- A four-channel charge-sensitive (CSA) preamplifier in *hole collection mode* with *synchronous reset*
- *Three different gains* to cover the energy range
  - Gain: 2.2, 1.1 and 0.36 mV/keV
- Power consumption of < 30 mW/channel
- *Leakage emulator & test pulse input*

- **Front-End Board (FEB):**

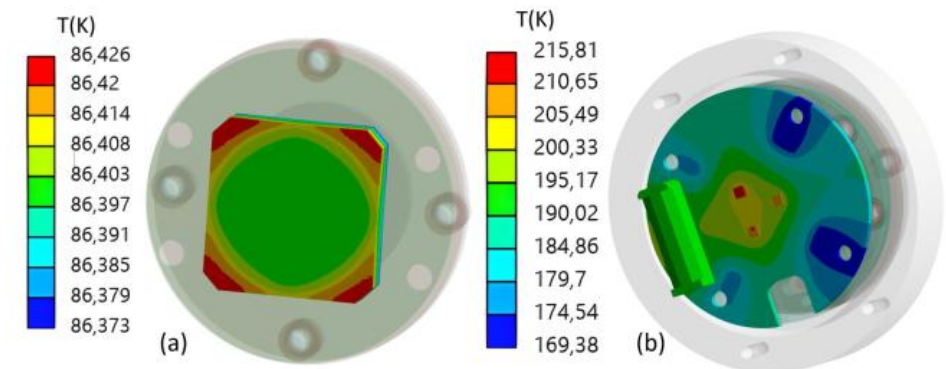
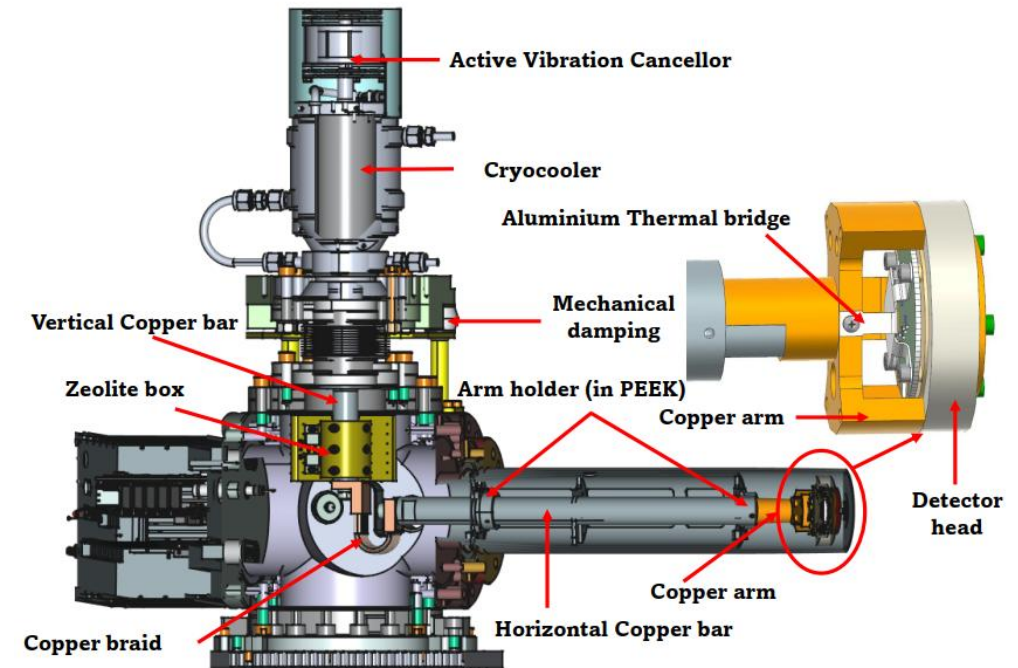
- Circular board made in *ceramics*
- Links *10 pogo pins pads* ( $\varnothing$  0.4 mm) on one side to *10 input channels* of 3 TETRA ASICs at other side
- FEB-BEB interconnected by a Kapton Flex PCB

- **Back-End Board (BEB):**

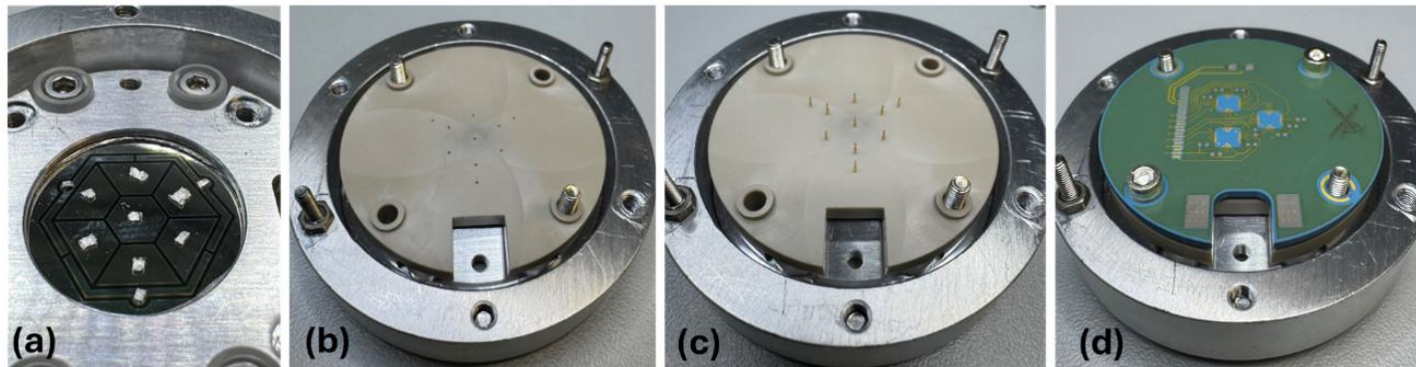
- It comprises three PCB boards designed to bias & configure 3 TETRA ASICs (*10 analogue signals*)
- The 10 signals are routed to 10 SMA connectors
- There are also 3 connectors:
  - 2 inputs: *external reset pulse* and *test pulse*
  - 1 output: *inhibit reset signal*



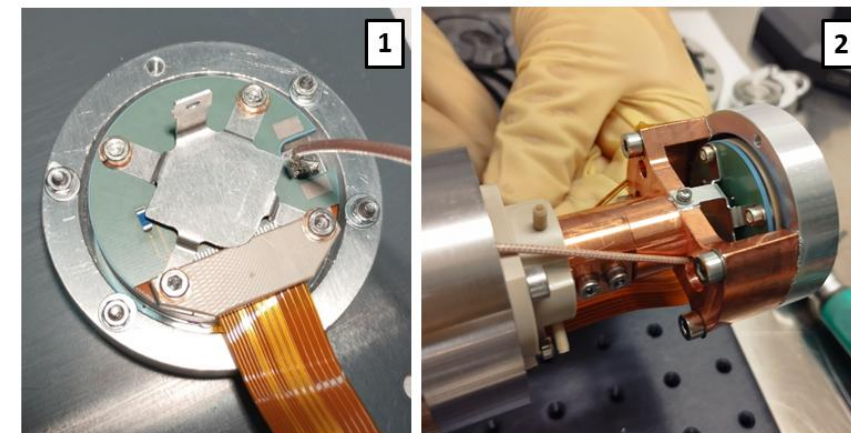
- Cooling system is based on an electrically Stirling-cycle cryocooler (model CryoTel by Sunpower).
- Vibrations are compensated by mechanical damping and thermal decoupling elements.
  - Maximum induced vibrations of 0.04-0.07 m/s<sup>2</sup> for frequencies above 50 Hz.
- Four thermometer (PT100) monitor temperature at copper arm, FEB, zeolite box and copper bar.
  - The first one works as a feedback device for cryocooler.
- A zeolite box attached to the vertical copper bar allows the operation in static vacuum.
- Mechanical design has been optimized by thermal simulations:
  - Cooling pipe is supported by two PEEK arm holders
  - An aluminium thermal bridge is the first path to evacuate the dissipated power from the FEB.



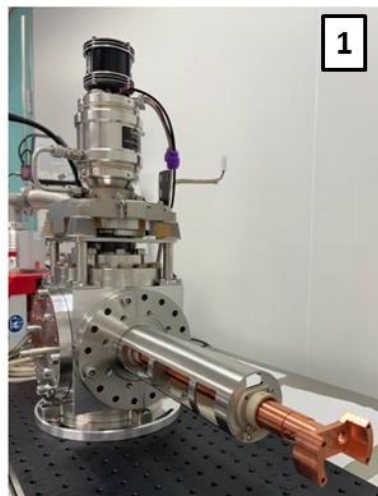
*M. Quispe et al., JACoW IPAC2024 TUPR75*



*Interconnection by pogo-pins and a peek holder*



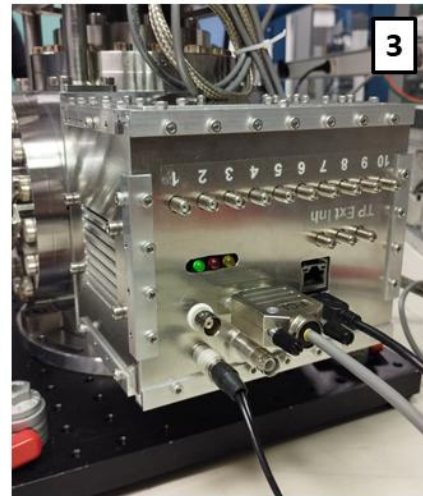
*Detector head assembly*



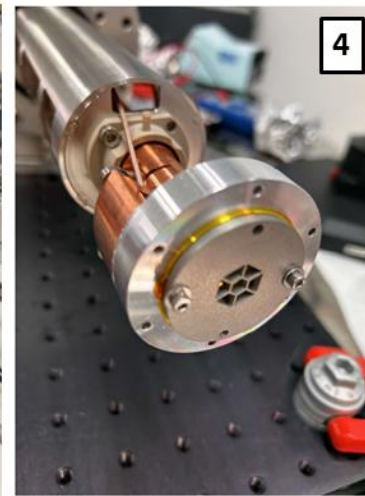
*Mechanical & cryostat assembly*



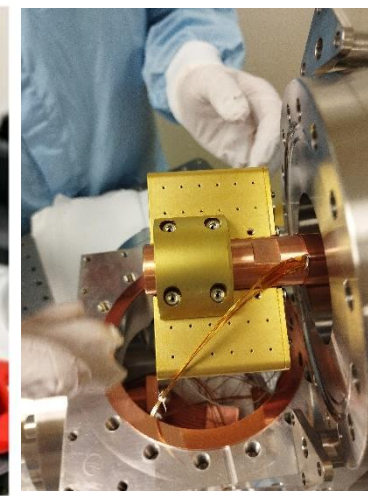
*Beryllium window*



*Electronics box*



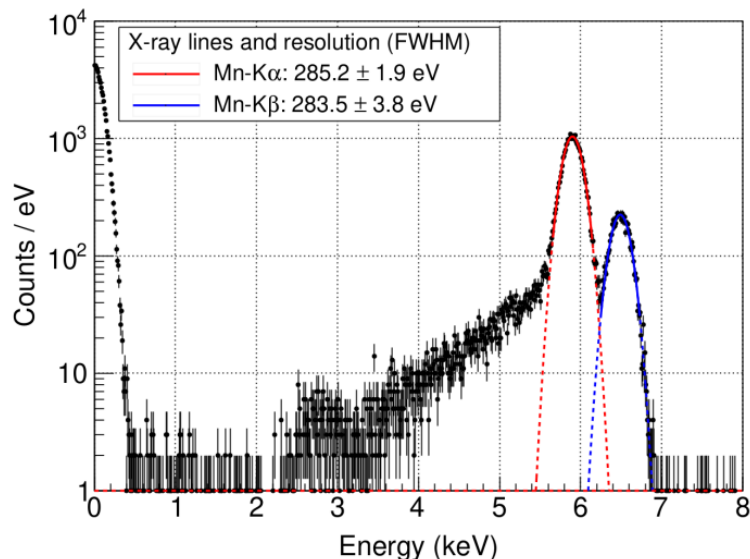
*Collimator*



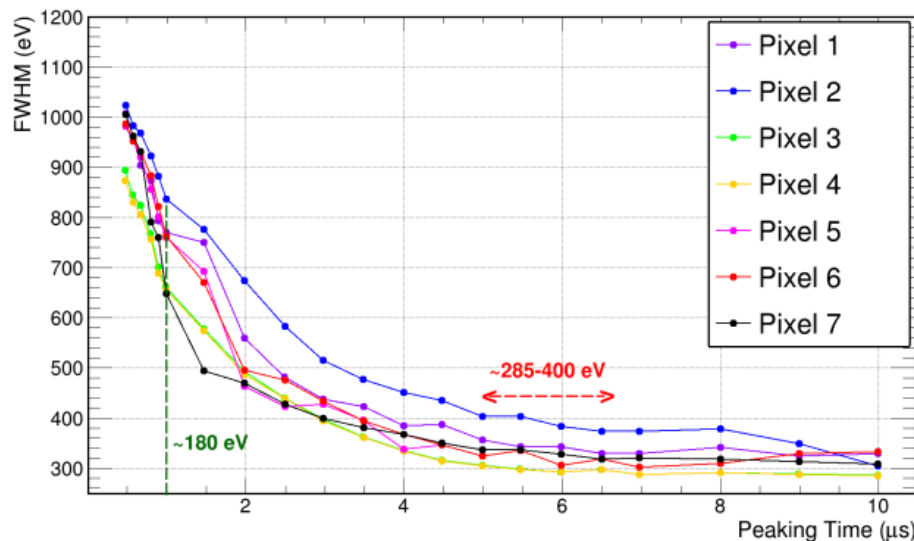
*Zeolite box*

- Performance tests done:
  - Laboratory: Fe55, Am241, X-ray generator
  - Lab  $\mu$ -spot X-ray beam + Beam test at ESRF
- Detector performance is not good enough for a synchrotron experiment
- Actual performance is limited by
  - Germanium sensors
    - Presence of **charge trapping defects**
  - Interconnection (pogo-pins)
    - Energy resolution results are compatible with an **input capacitance of 4 pF** and a high flicker (1/f) noise

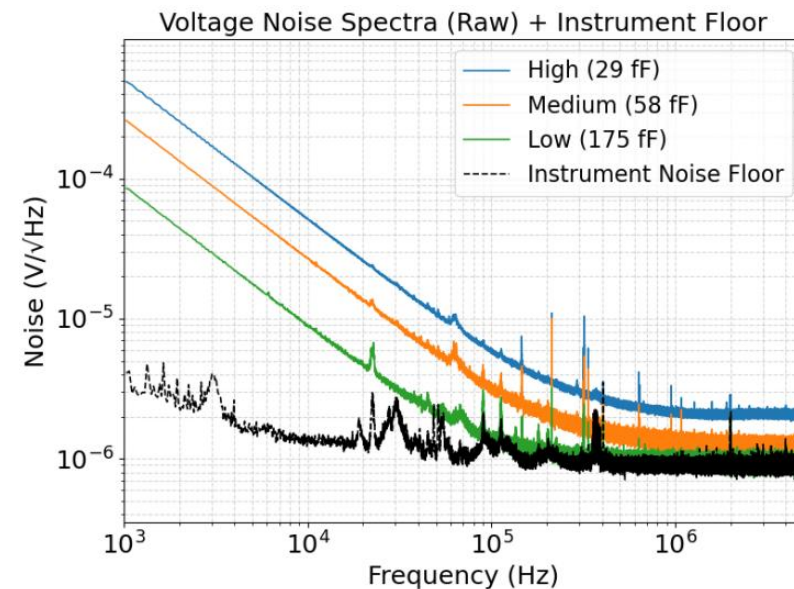
Specification	Expected Value	Achieved Value
Sensor temperature	77°K	<b>76°K</b>
Pre Gain	~2.0 mV/keV	<b>1.99-2.06 mV/keV</b>
Resolution @5.9keV	180 eV (1 $\mu$ s)	<b>258-400 eV (6<math>\mu</math>s)</b>
Resolution @59.5keV	350 eV (1 $\mu$ s)	<b>450-510 eV (6<math>\mu</math>s)</b>
Dead time	< 10% at 1 Mcps	<b>Saturation at 150-200 kcps</b>
Charge trapping	No	<b>Yes (6 defects)</b>
Cross-talk ratio	<0.2% (sim)	<b>0.02-0.04%</b>
Fall time	< 50 ns	<b>42 ns at 300 V</b>



**Fe-55 source**

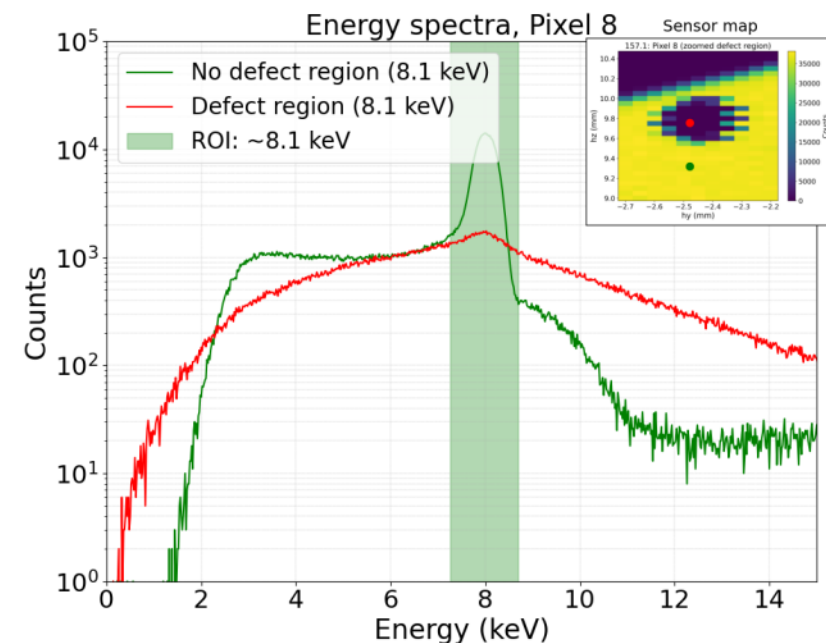
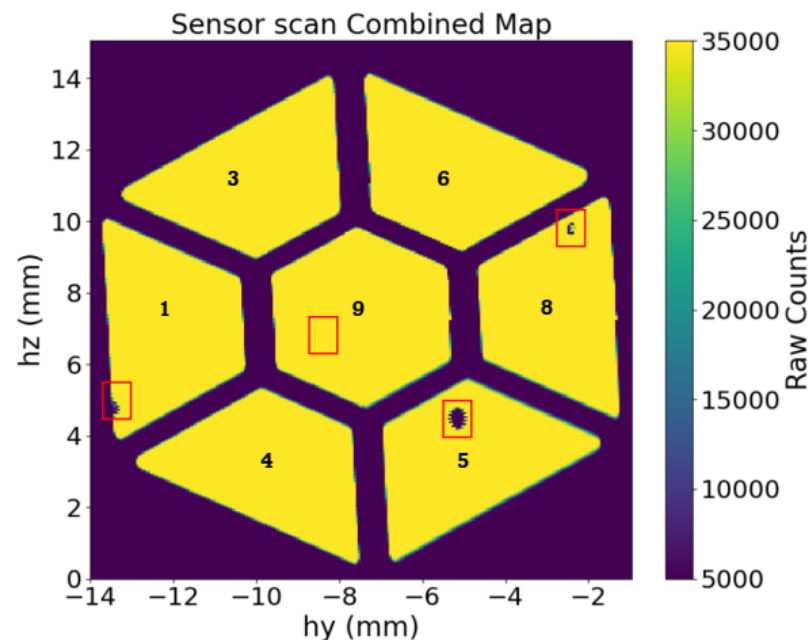
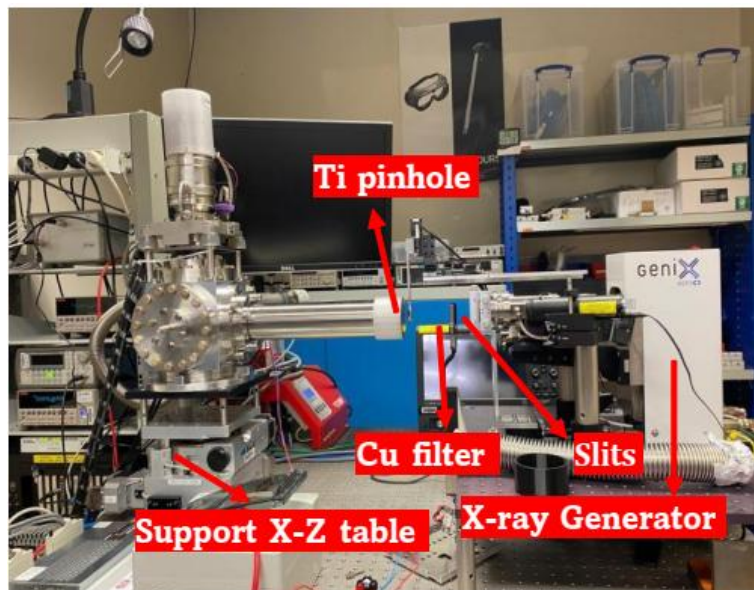


**Resolution at 5.9 keV**



**Power Spectra Density**

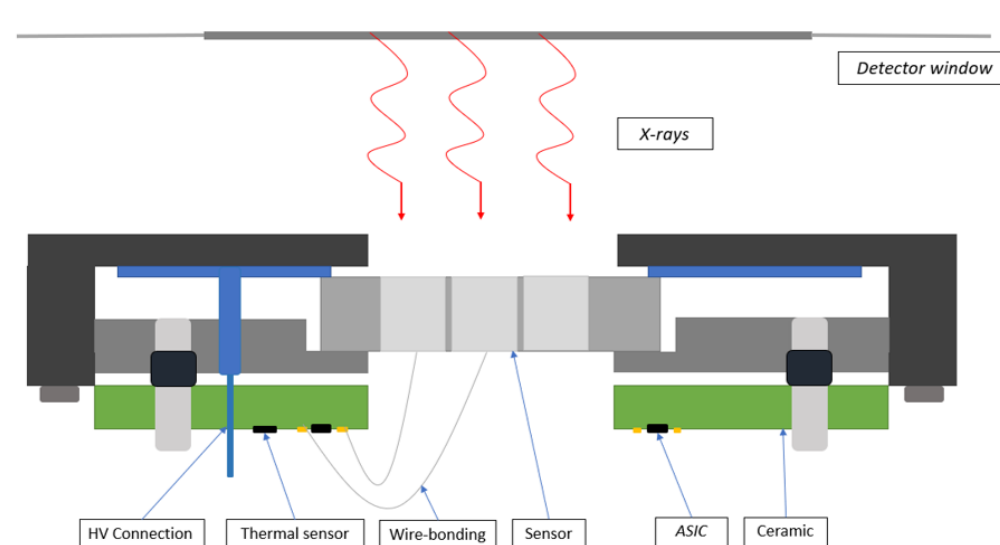
- Energy resolution evaluated with Fe-55 (5.9 keV) & Am-241 (59.5 keV) + DANTE DPP (trapezoidal filter)
  - Optimum at 6 us : 285 eV (FWHM) at 5.9 keV & **445 eV (FWHM) at 59.5 keV**
  - Slightly improvement down to **258 eV (FWHM) at 5.9 keV** with better electronics housing
- Noise components evaluated by Power Spectral Density (Data translation DT9862)
  - PSD rises at low frequencies due to **high voltage noise**, i.e., **high capacitance (~4 pF** : pixel + pogo-pin + FEB path)
  - Several **Flicker-noise components** appear between **140 and 320 kHz**



- Spatial response studied at ESRF's detector unit laboratory
  - X-ray beam: **8.04 keV (Copper),  $\varnothing 100 \mu\text{m}$**
  - Mapping of surface: **50  $\mu\text{m}$  step, 1 sec** exposure time
- Pixel boundaries closely match the molybdenum aperture -> Good alignment
- Four distinct regions with reduced sensitivity were detected
  - Defective areas in germanium sensor -> High leakage current -> **Charge trapping defects at frontside surface**
  - More defects observed at higher X-ray energy. Same result for second sensor from MIRION



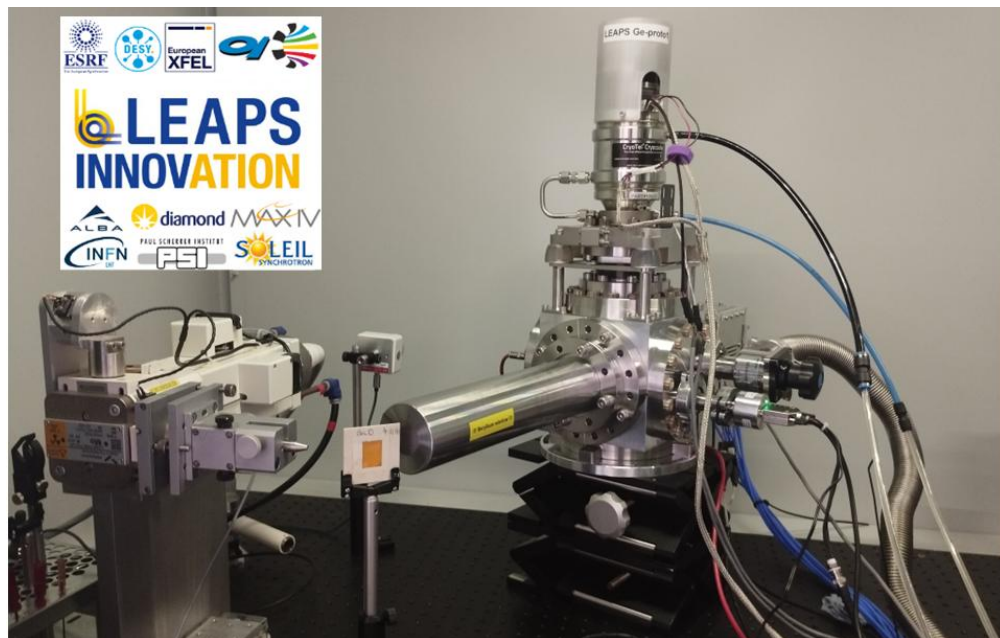
Brookhaven  
National Laboratory



Concept of wire-bonding interconnection on LEAPS sensor

Chouaib Meraihia (ESRF)

1. Three new germanium sensors from Brookhaven National Laboratory (Abdul Rumaiz)
  - Germanium technology: 1) trenched edges, 2) amorphous Germanium for front-side window
  - Good spectroscopy properties demonstrated by BNL collaborators in Gepta-EX prototype.
  - Status: Fabricated. IV curve test mid-June. Shipment to ESRF in July.
2. Test of wire-bonding sensor-FEB interconnection
  - New FEB design by ESRF for wire-bonding. Design ready in July 2026.
3. Optimization of the thermal link to reduce ASIC temperature & further reduce noise level



- LEAPS is a new multi-element monolithic germanium detectors for XRF/XAS.
- The first prototype has been fabricated & characterized in only 4.5 years!
- Actual degraded spectroscopy performance is due to charge trapping in germanium sensors and the high capacitance of interconnections.
- These problems will be fixed by end 2026.

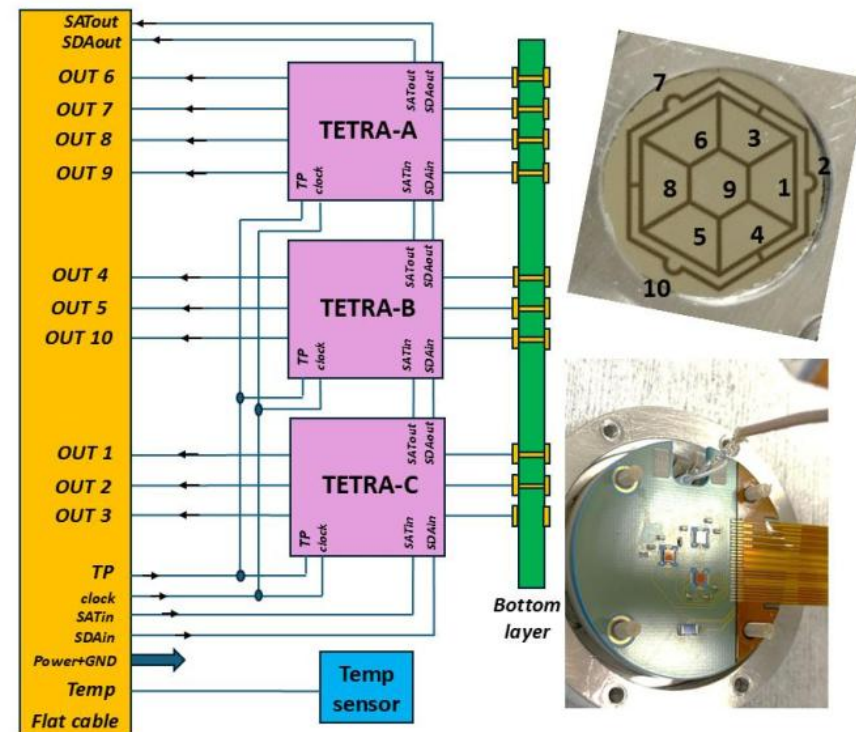
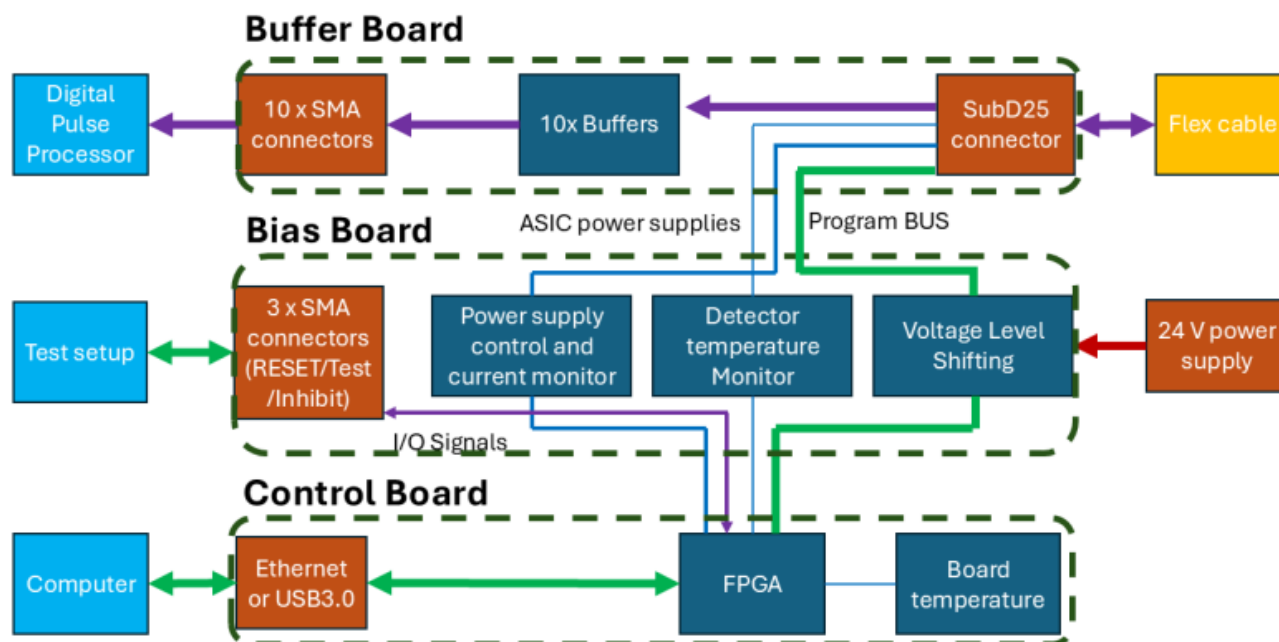
***Thanks for your attention! Questions?***

**Thank you for your attention. Questions?**



# Back-up slides





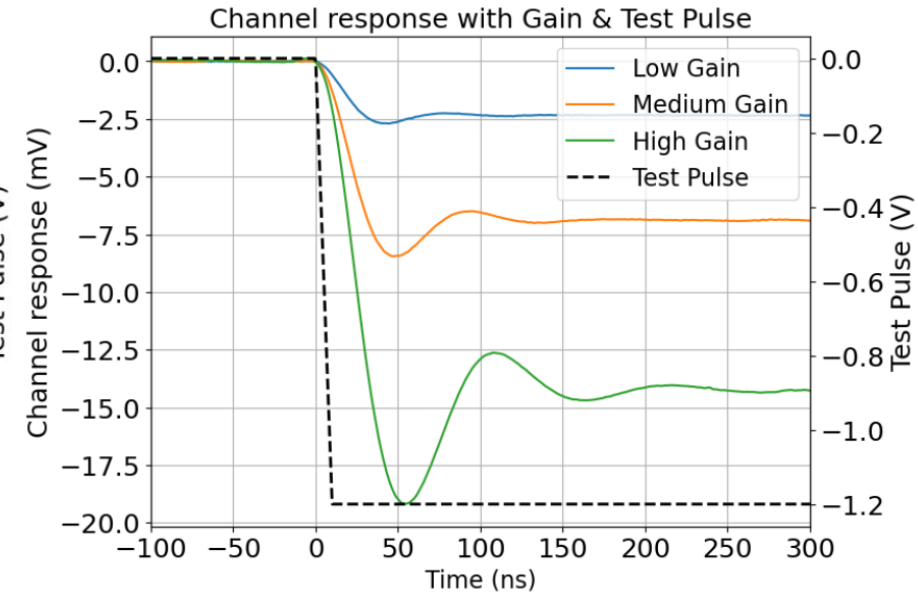
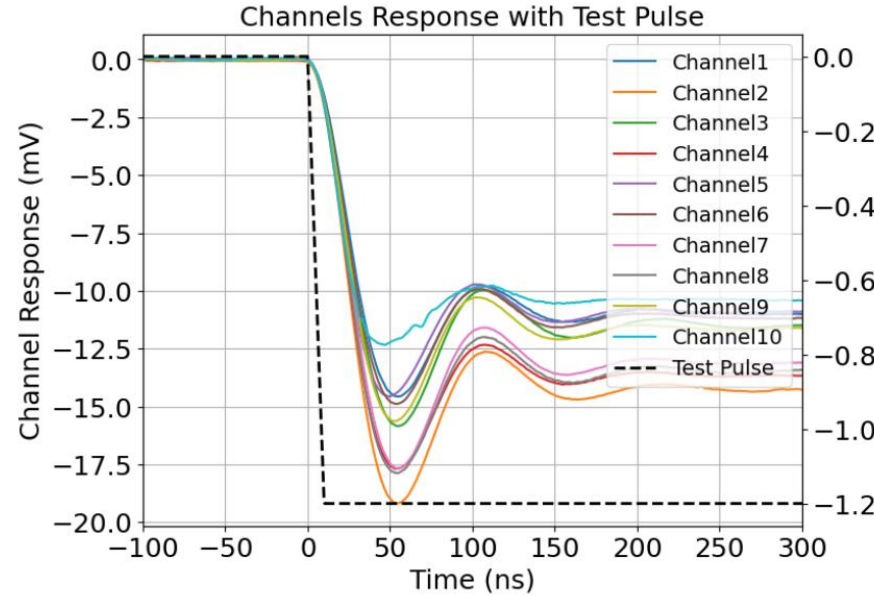
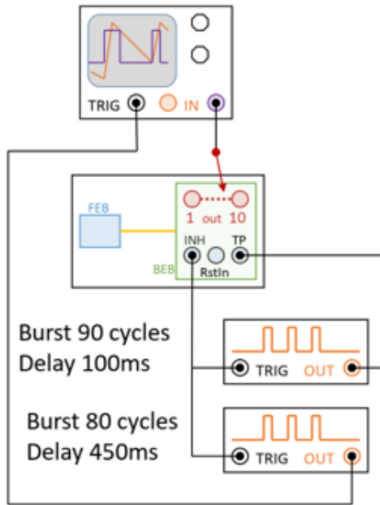
## *BEB system is composed of three boards:*

- **Buffer board:** Analog signals are buffered and transmitted to the other boards.
- **Bias board:** It provides all power supplies to ASICs & boards. It also monitors the detector temperature.
- **Control board:** It monitors and controls all features.

Oscilloscope  
 - Coupling AC  
 - Average summed 1000

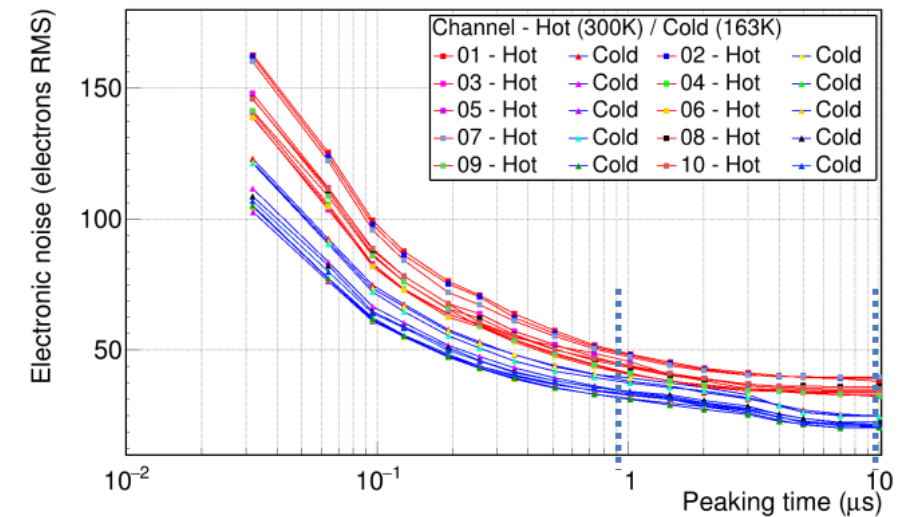
FEB BEB  
 - Leakage OFF  
 - All channel Enable  
 - Rth ? (low)  
 - RPW 4

Generators  
 - Amplitude 1V  
 - Period 35ms  
 - Pulse 5ms  
 - Rise time 10ns



## Tests made at room (293°K) & cold temperature (163°K)

1. Ramps waveforms, gain settings, channel enable/disable
2. RESET response (duration, threshold): **0.7-5.9  $\mu$ s**
3. Signal fall time: **19-23 ns (312°K), 15-21 ns (136°K)**
4. ENC (using DANTE DPP):
  - At 1  $\mu$ s: **36-45 elec rms (312°K), ~30 elec (136°K)**
  - At 10  $\mu$ s: **29-35 elec rms (312°K), ~20 elec (136°K)**
5. Outgassing rate: **7 x 10<sup>-7</sup> mbar lit/sec + RGA test**

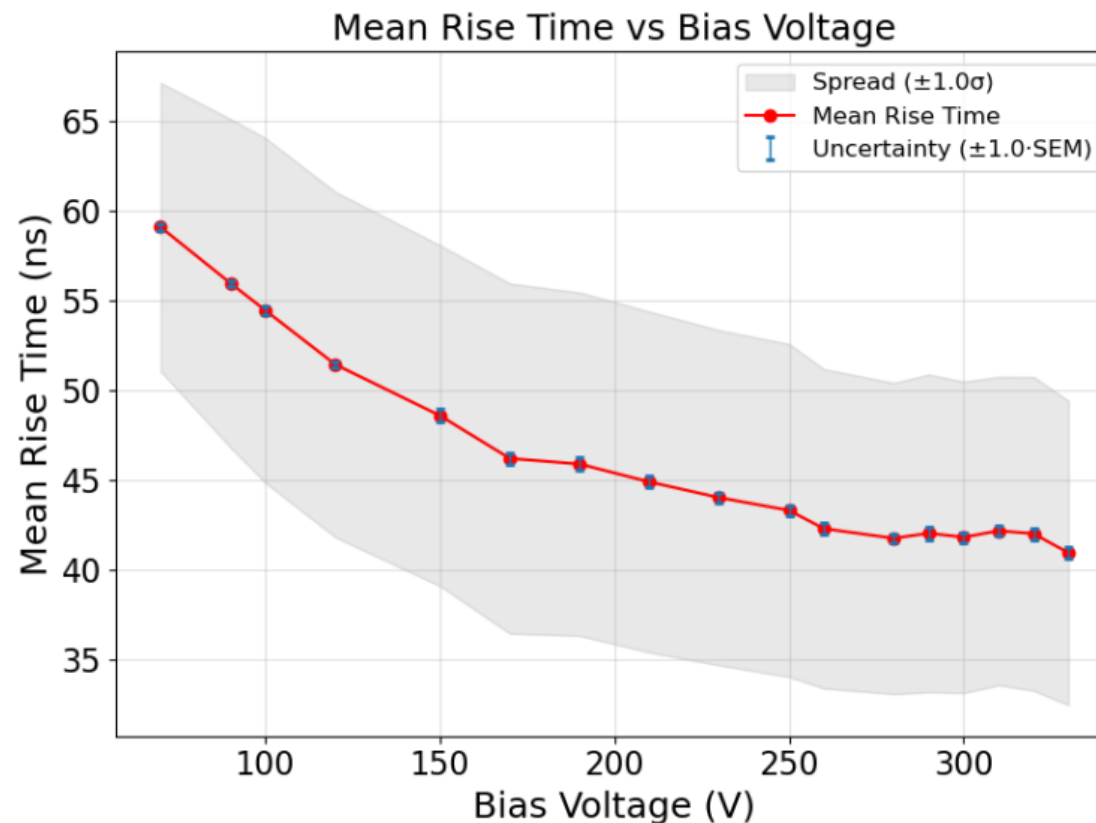


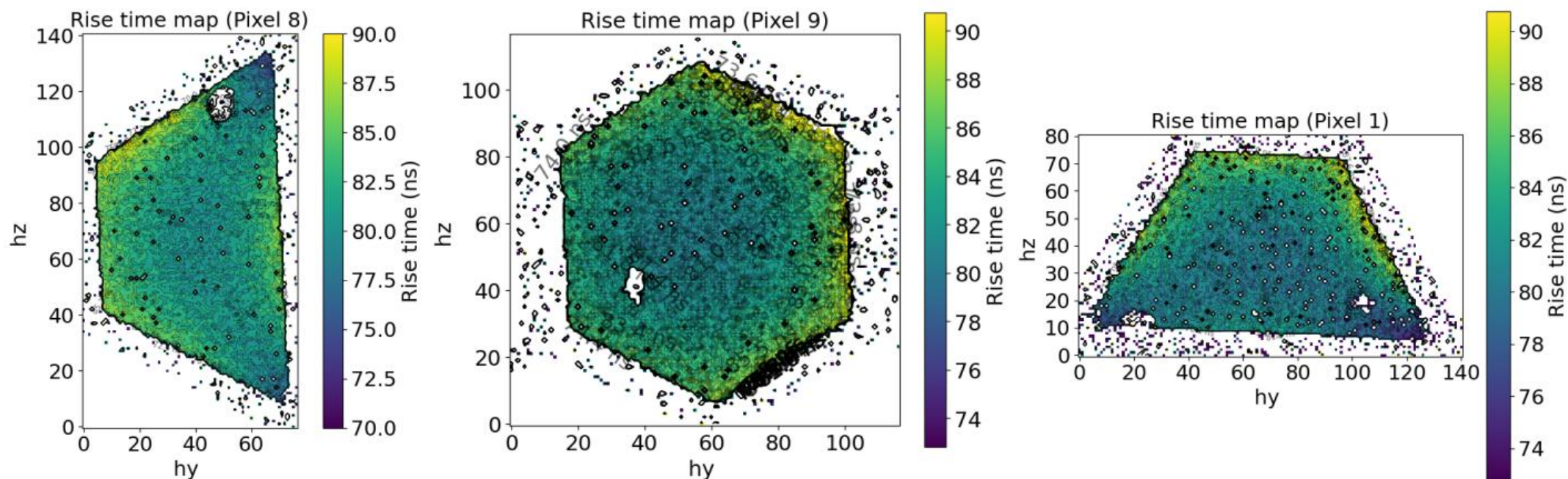
## Methodology:

- Fe55 source, low flux (10 kcps)
- 100k waveforms using oscilloscope (1 ns res)
- Bias voltages from +50 to +300 V
- Analysis: signal amplitude & risetime

## Results:

- Gain: **1.99-2.06 mV/keV**
- Risetime shifts to shorter values (higher hole drift velocity at stronger electric fields)
- Saturation at **42 ns (280-330 V)**

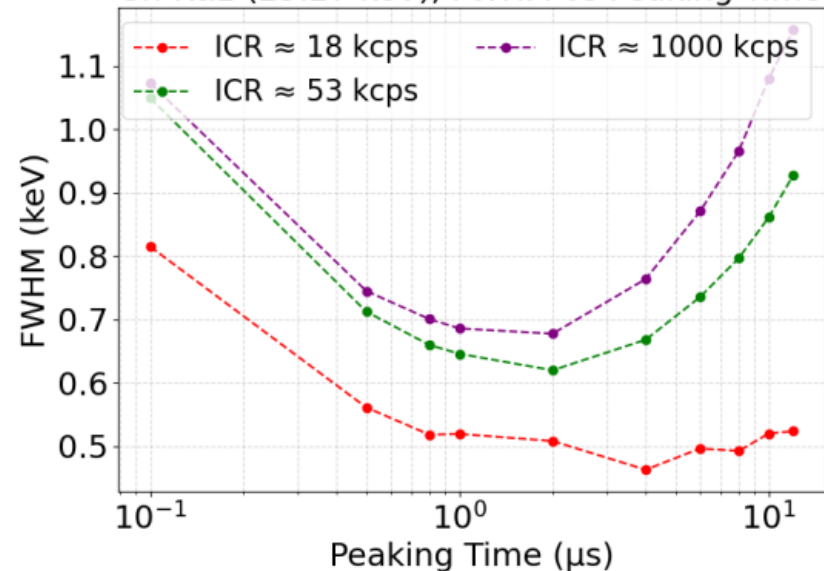




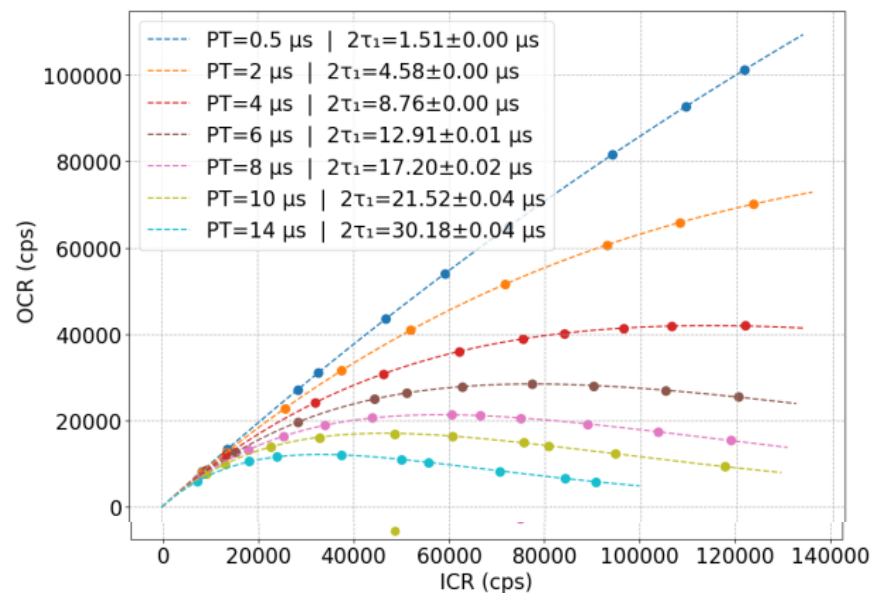
**Bias Voltage = +70V**

- Signals waveforms acquired by a digital oscilloscope coupled to electronics.
- Average **risetime of 80 ns at +70 V**, consistent across the pixel surface.

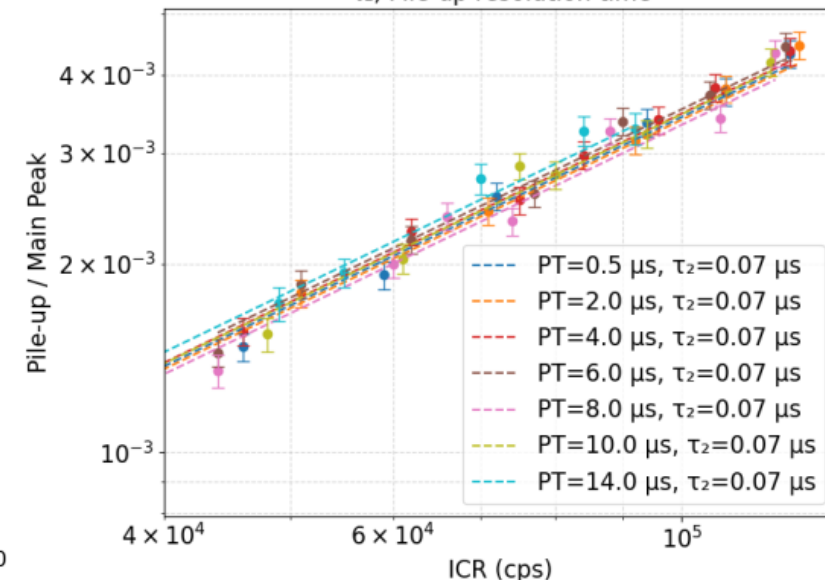
Sn-K $\alpha$ 1 (25.27 keV), FWHM vs Peaking Time



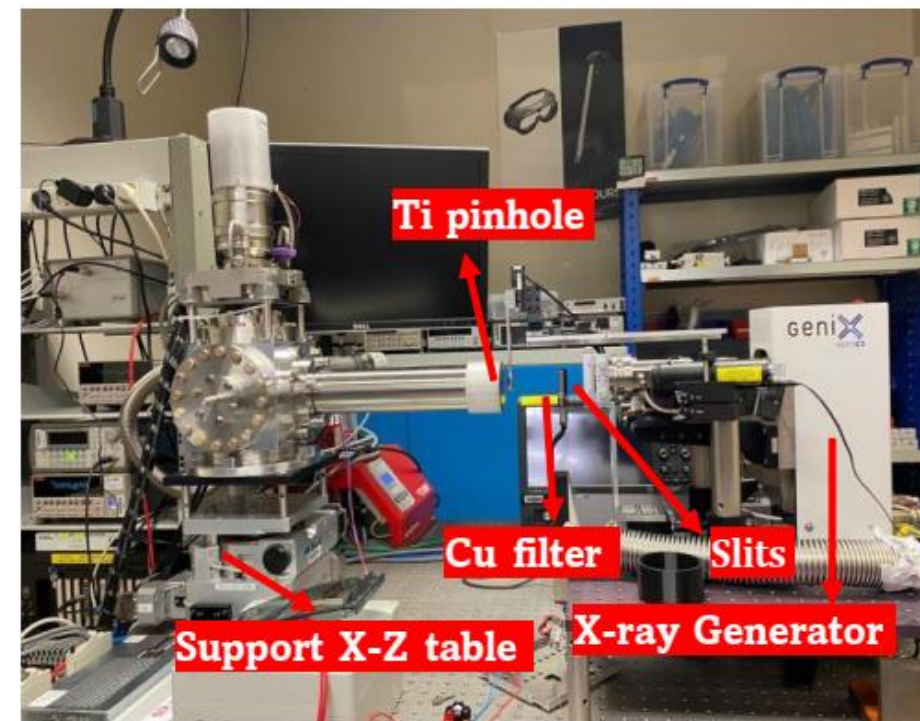
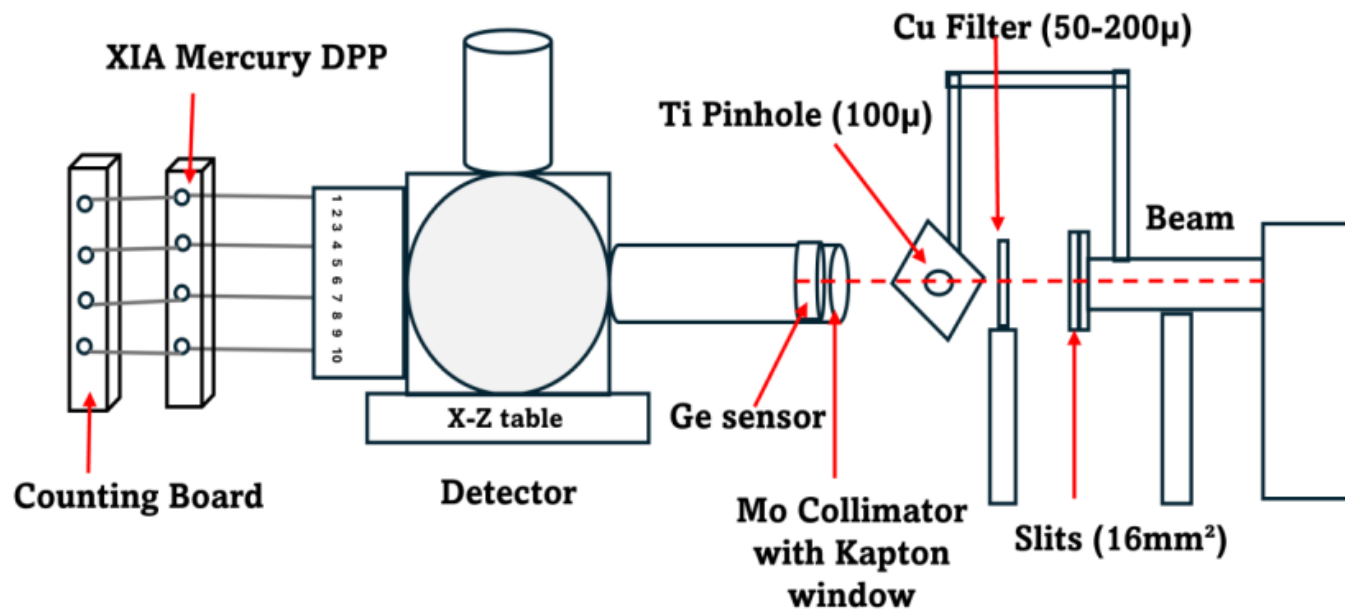
OCR model fits:  $OCR = ICR e^{-2\tau_1/ICR}$



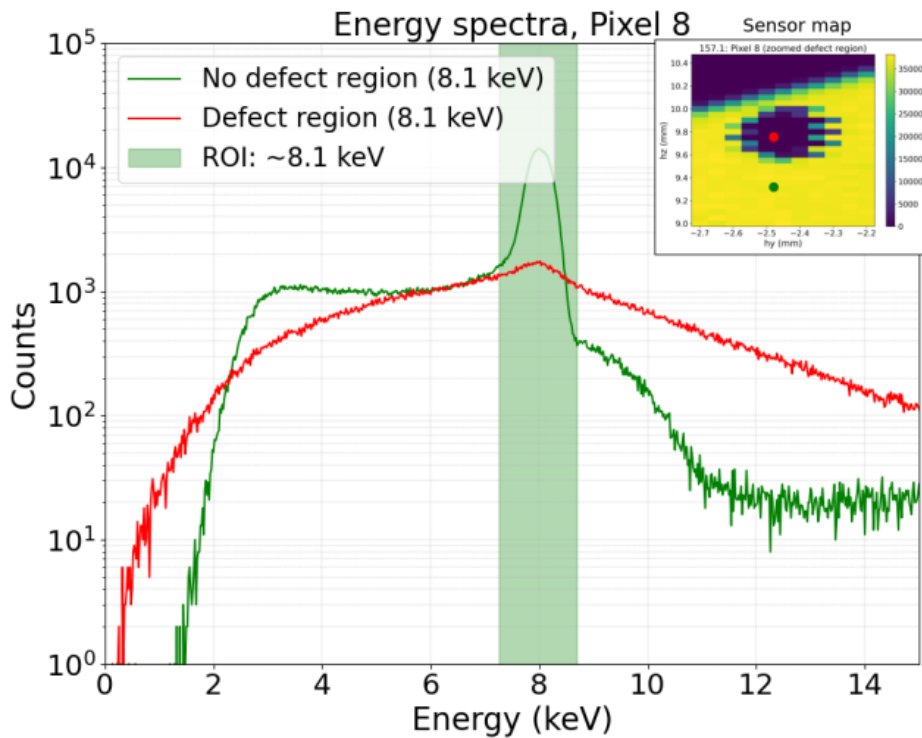
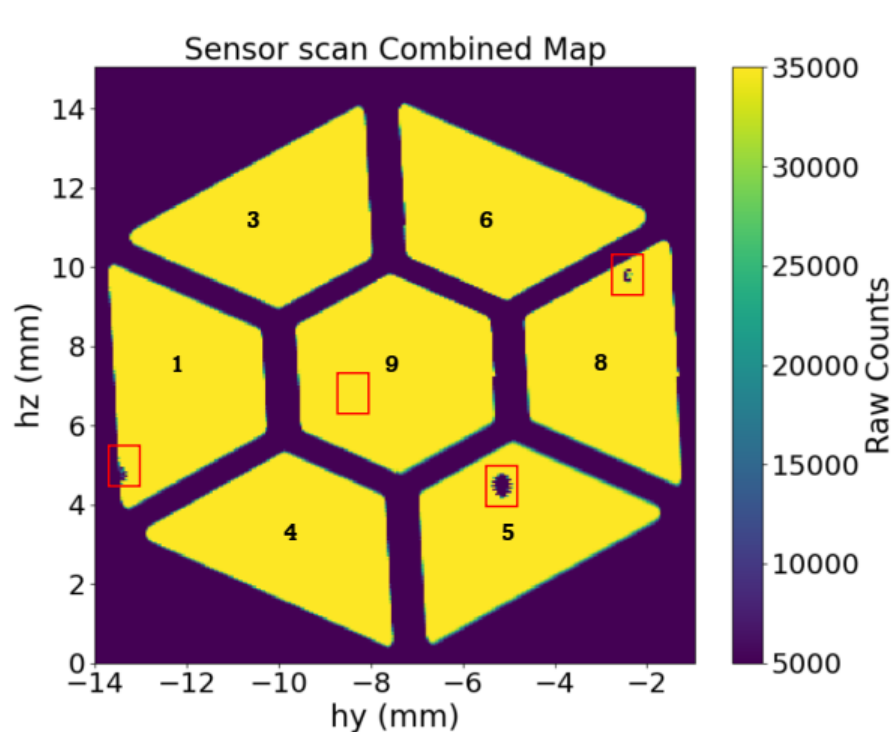
$\tau_2$ , Pile-up resolution time



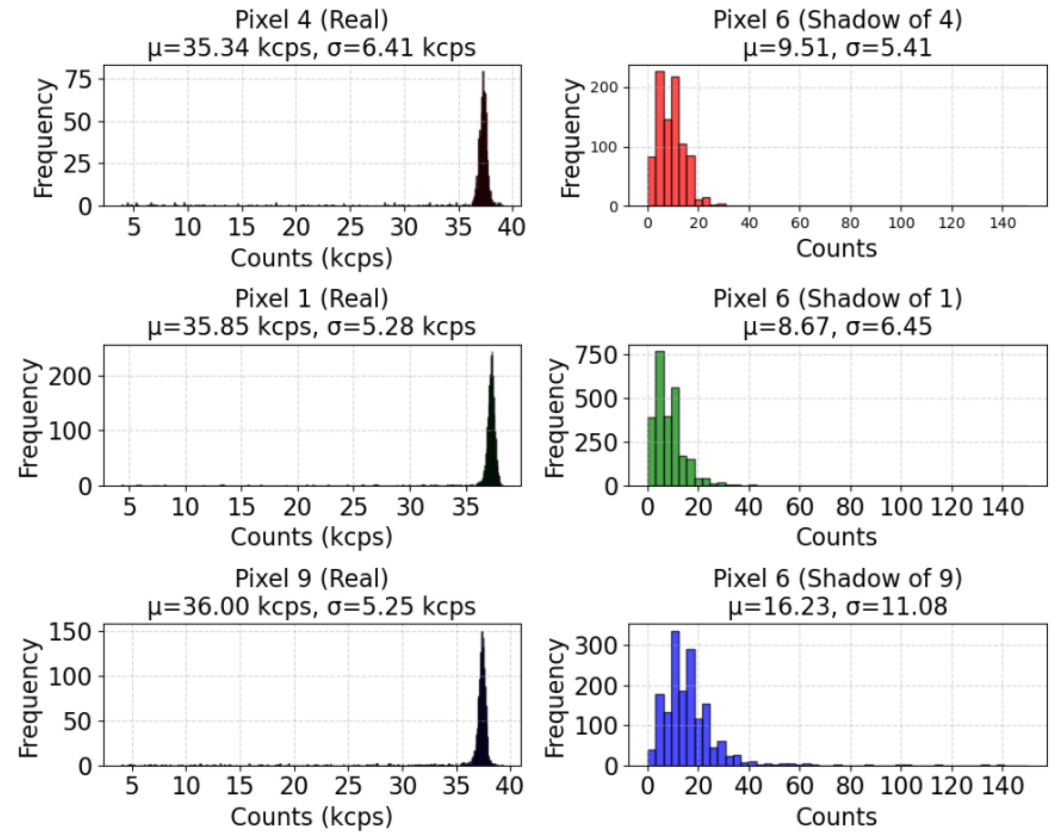
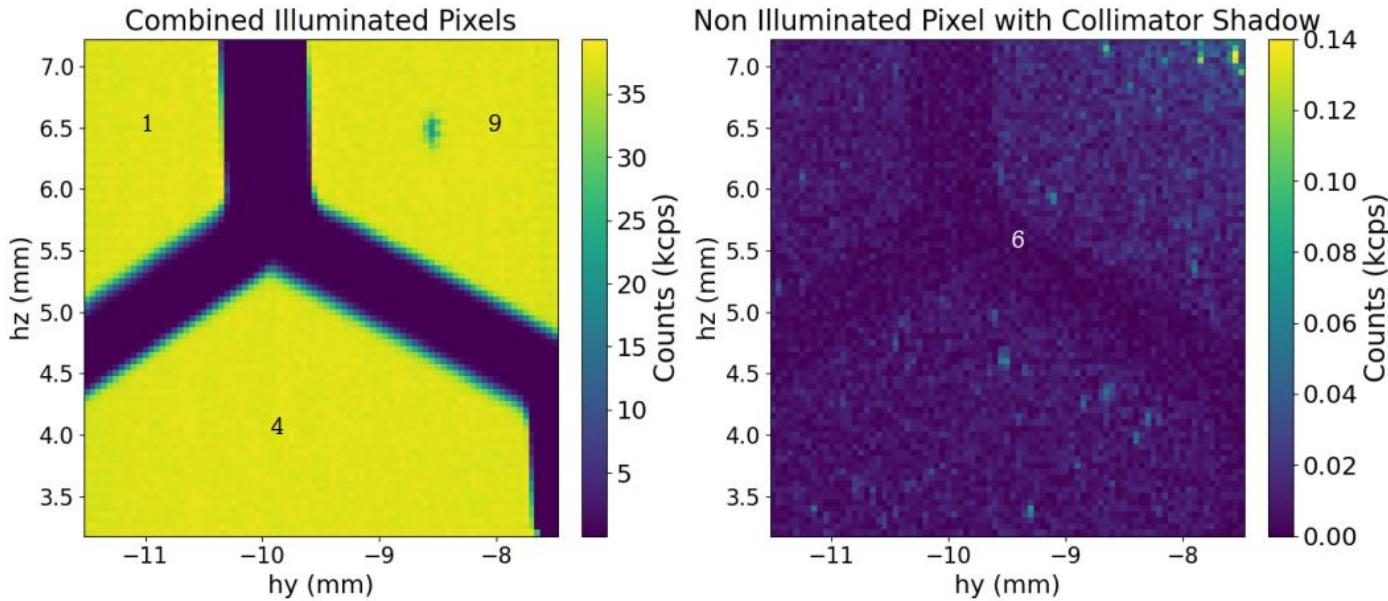
- Fluorescence spectra for Mn (5.9 keV), Sn (25.27 keV) & Ba (32.1 keV) + DANTE DPP
- Evaluation of energy resolution, dead time and pile-up intensity
  - Optimum performance at peaking time of 4-6 μs. At higher ICR, optimum shifts to 1 μs.
  - Dead time: 13 μs at PT = 6.0 μs (*saturation* ~30-40 kcps), 2.5 μs at 1.0 μs (*saturation* ~150-200 kcps)
  - Low pile-up intensity: 70 ns resolution time



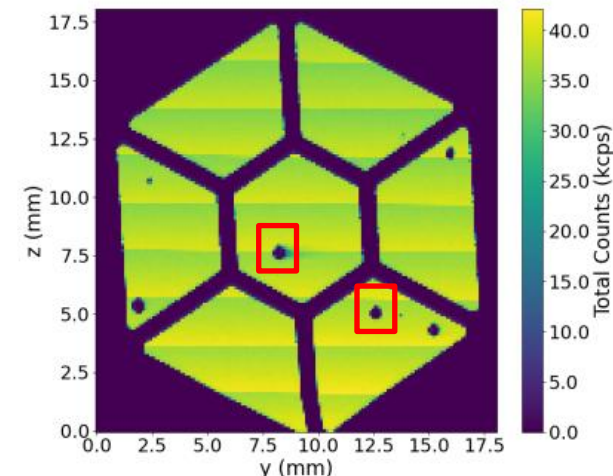
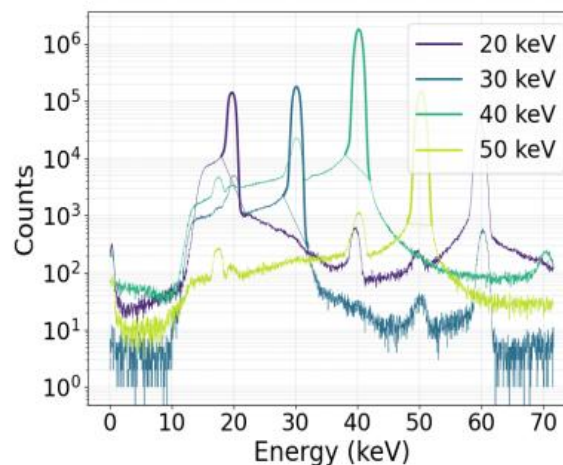
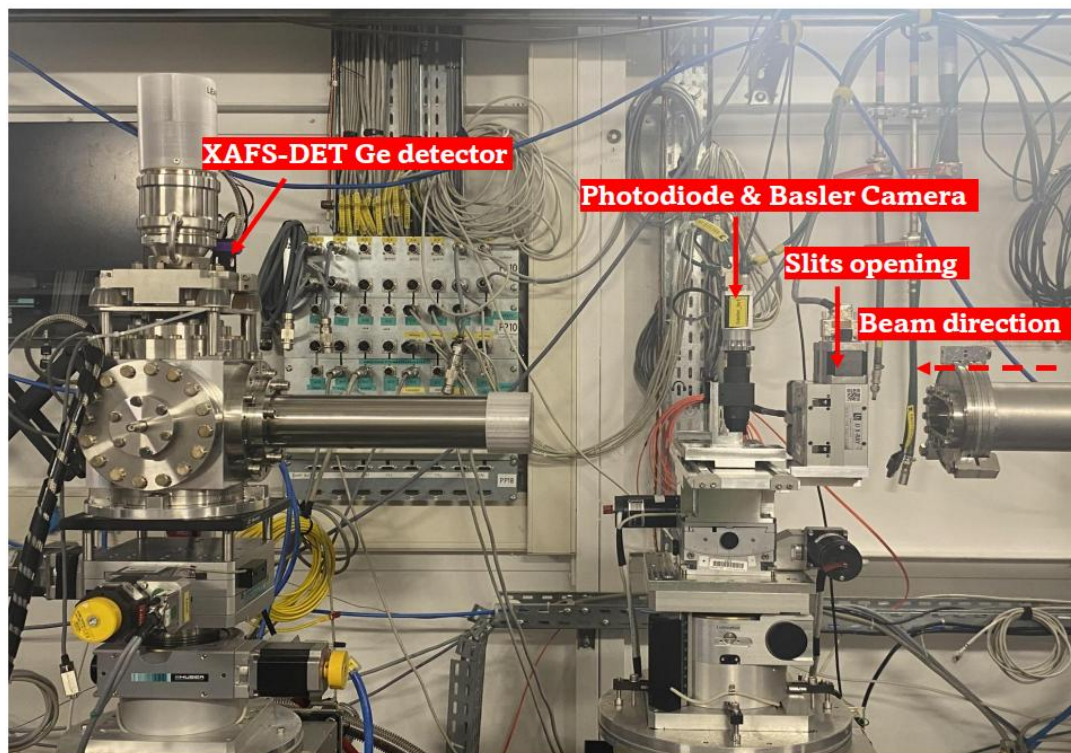
- Spatial response studied at ESRF's detector unit laboratory
- X-ray beam: **8.04 keV (Copper),  $\varnothing 100 \mu\text{m}$**
- Mapping of surface: **50  $\mu\text{m}$  step, 1 sec exposure time, 4-5 scans (3-4 pixels/scan)**
- Performance results: 1) surface (counting) response, 2) risetime, 3) pixel cross-talk



- Pixel boundaries closely match the molybdenum aperture -> Good alignment
- Four distinct regions with reduced sensitivity were detected
  - They correspond to defective areas in germanium sensor
  - The leakage current increased from 1 to 100 pA when illuminated (30-35 kcps)
- Uniform spatial response: dispersions 1% (pixel 5), 17% (pixel 9)

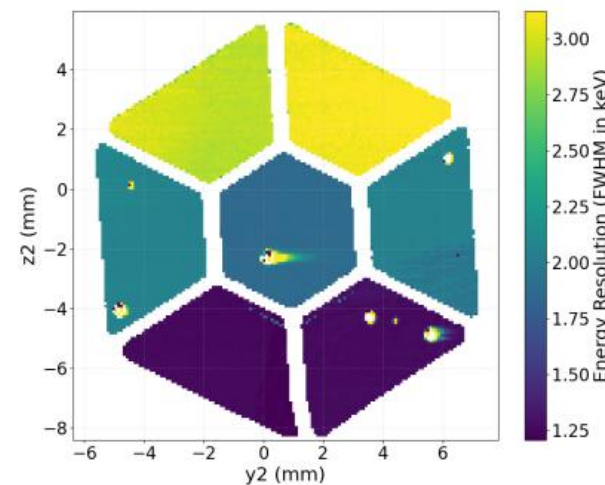


- In some scans, one non-illuminated pixel was connected to electronics.
- The pixel registered a faint shadow of the collimator, sign of cross-talk.
- Measured **cross-talk: 0.024% to 0.045%** (below 0.2% sim)



(a)

(b)



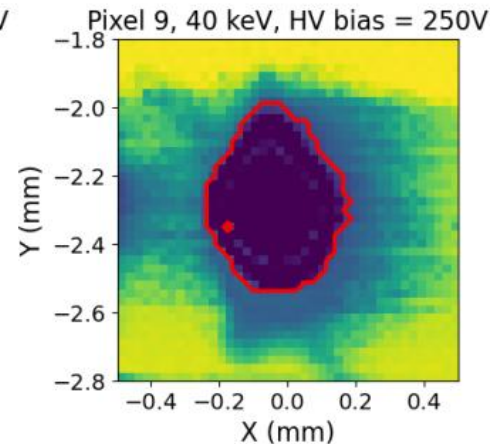
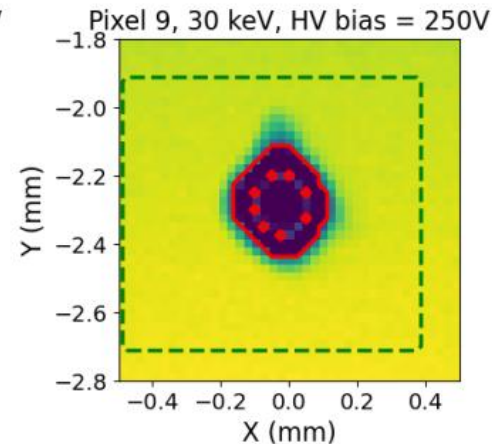
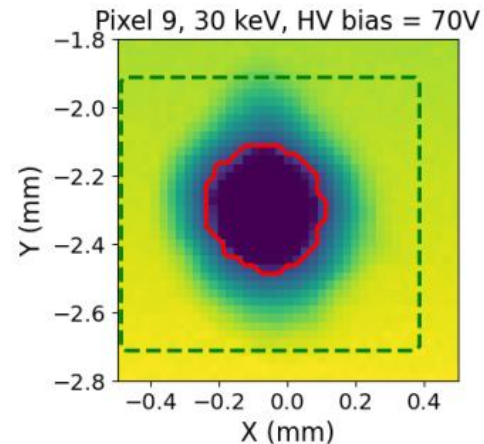
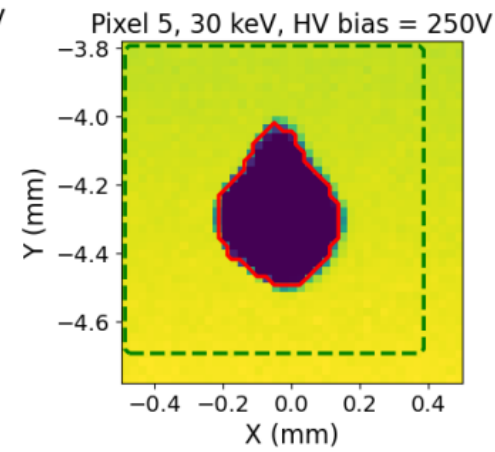
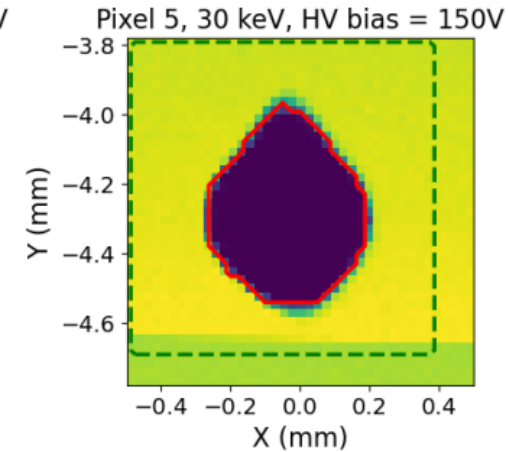
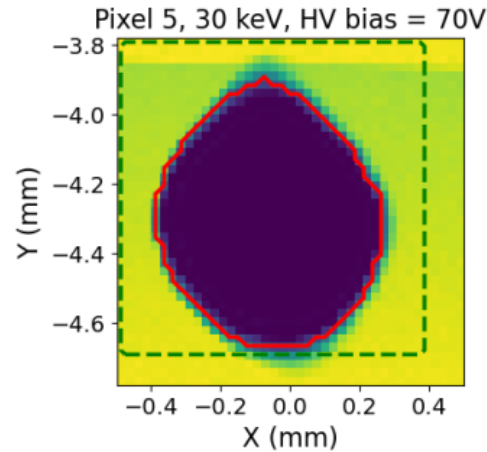
- Two-dimensional spatial response maps at X-ray energies between 20-50 keV
- Beam spot: 35  $\mu\text{m}$ , step size: 250  $\mu\text{m}$ , 25  $\mu\text{m}$
- And some fluorescence spectra (not shown here)

- High-resolution scans on the defective areas of pixels 5 & 9 at three different bias voltages.
  - Defect size reduces with bias voltage
  - Defect size increases with X-ray beam
- Model for the suppression of X-ray intensity at the defects:

$$S(d) = e^{-\mu(E)d} \cdot \left(1 - e^{-d/\lambda_{\text{eff}}}\right)$$

- D: Depth  $\lambda_{\text{eff}}(V) = \lambda_0 \cdot (1 + \alpha V)$
- $\mu(E)$ : Absorption
- $\lambda_{\text{eff}}$ : Mean drift length of charge carriers in the sensor

- Defect depth estimated by numerically inverting: **1-6  $\mu\text{m}$**



## Energy resolution

$$Res(eV FWHM) = 2.35 \times \sqrt{(E \times F \times W) + ENC^2}$$

## Noise level

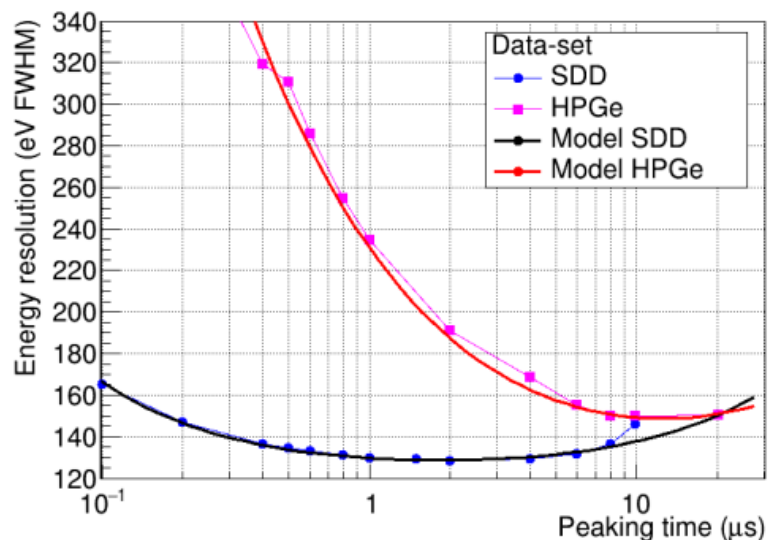
**Fano factor Noise level**

$$\left(\frac{ENC}{W}\right)^2 = (2 \times Q_e \times I_B \times \tau) + \left(C_D^2 \times \sigma_V^2 \times \frac{F_V}{\tau}\right) + (A_f \times F_{1F} \times C_D^2)$$

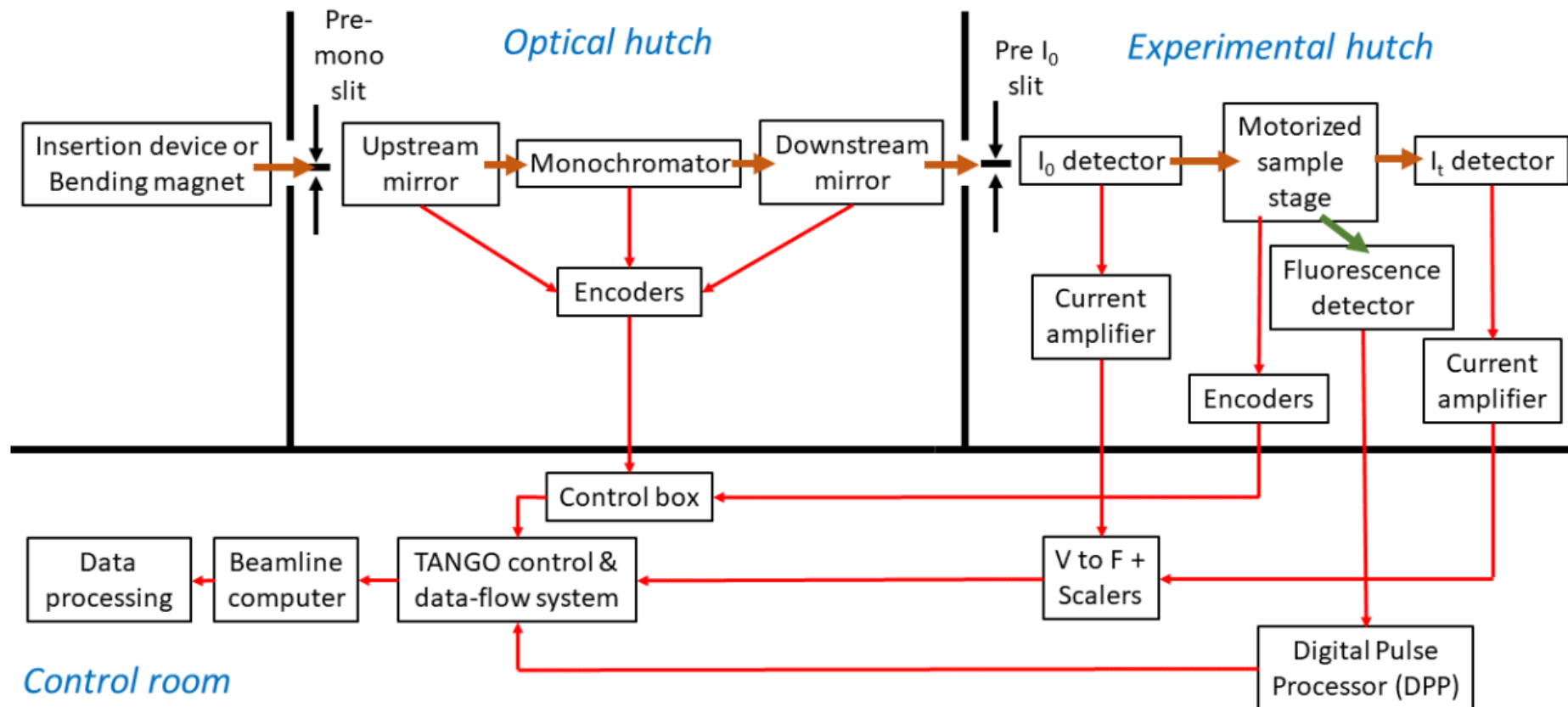
**Current noise**

**Voltage noise**

**Flicker noise**



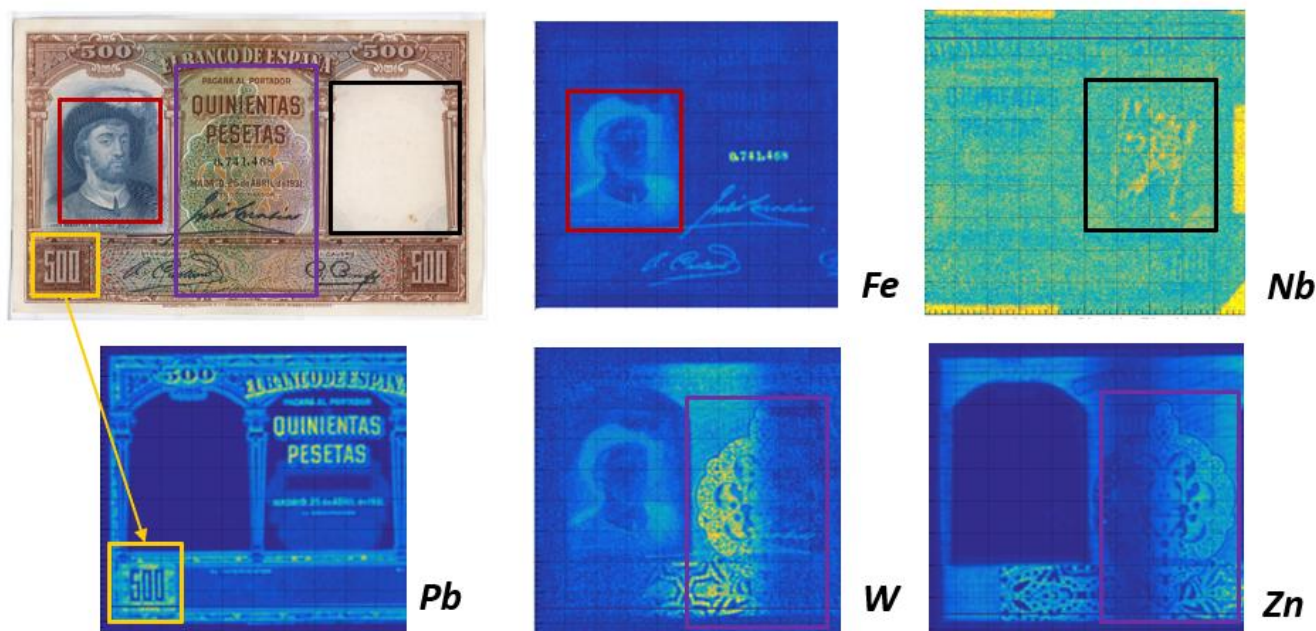
Symbol	Name	SDD	HPGe
$W$	Pair production energy	3.16 eV	2.9 eV
$C_D$	Detector capacitance	1.1 pF (0.2 pF)	7.5 pF (2.0 pF)
$\tau$	DPP shaping time	0.1-20 μs	
$I_B$	Leakage current	1.2 pA	1.2 pA
$F_I$	DPP current shape factor	0.333	
$I_B$	Spectral noise voltage	0.5 nV/SHz	
$F_I$	DPP voltage shape factor	1.0	
$I_B$	1/f voltage noise	100 fV	
$F_I$	DPP 1/f shape factor	0.5	



- **XRF:** Sample position is changed by a motorized stage.
- **XAS:** Energy is changed by monochromator.

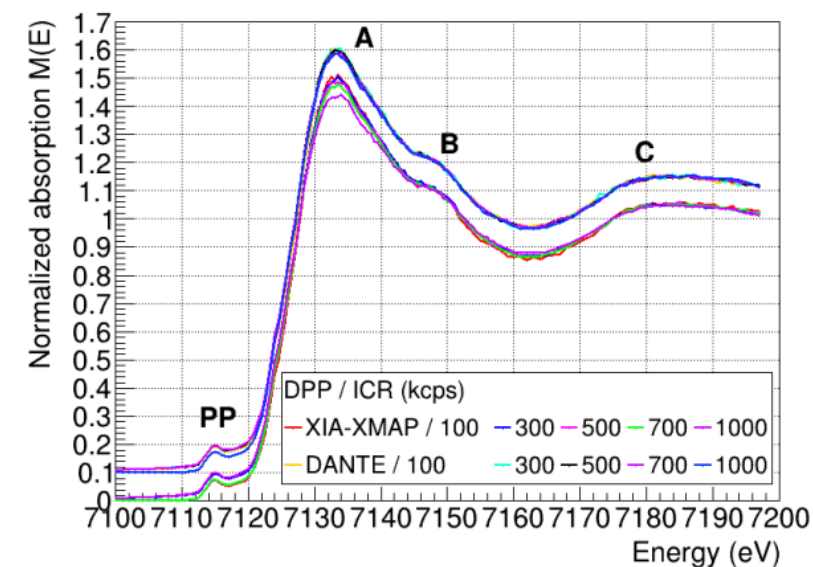
## X-ray Fluorescence (XRF)

- Fluorescence signal of a sample is measured after an excitation by incident X-ray photons at a given energy.
- The energy of the fluorescence signal depends on the element (e.g.: 6.4 keV for iron, 10.5 keV for lead).
- Signal intensity is proportional to the concentration.
- Combined with a micro-beam, an element map can be collected by scanning the sample position.

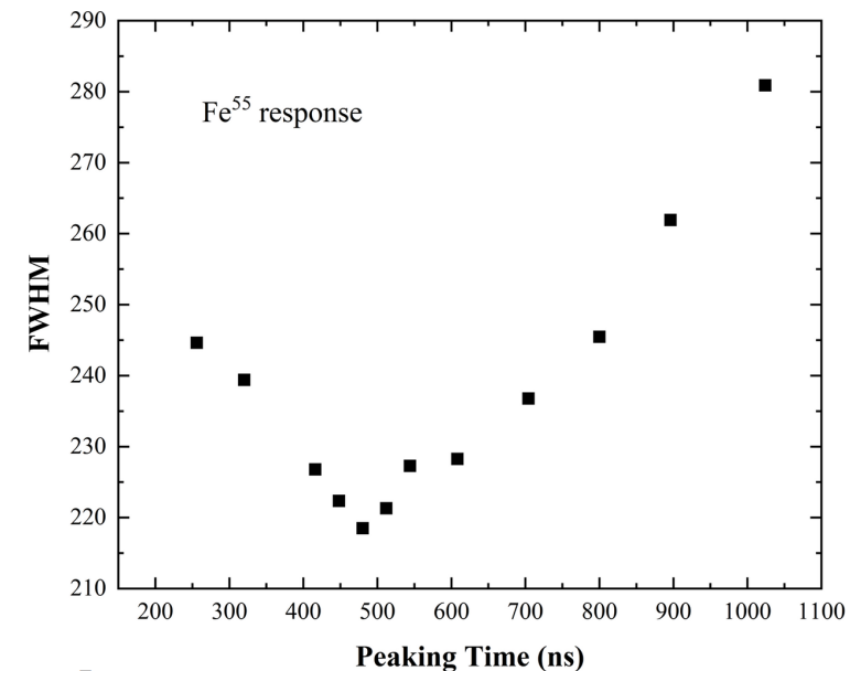
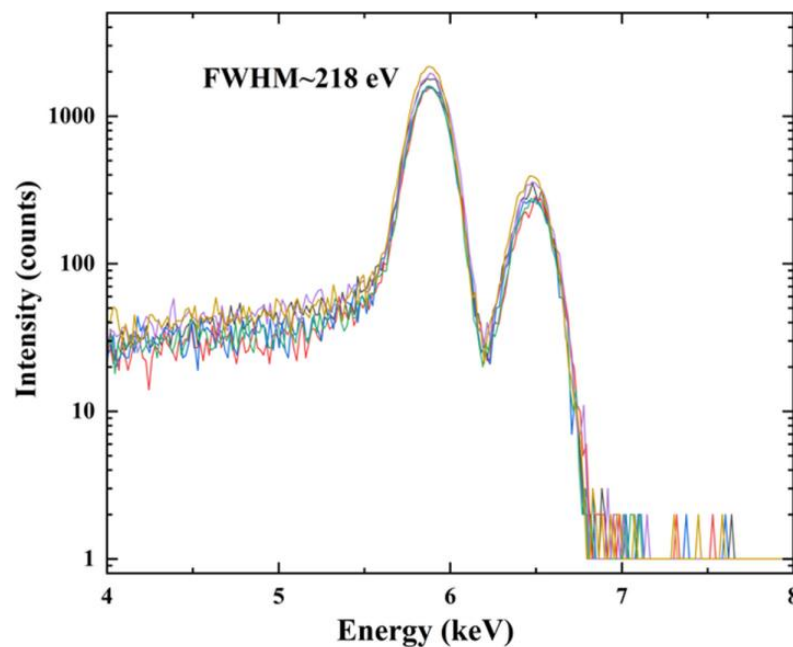
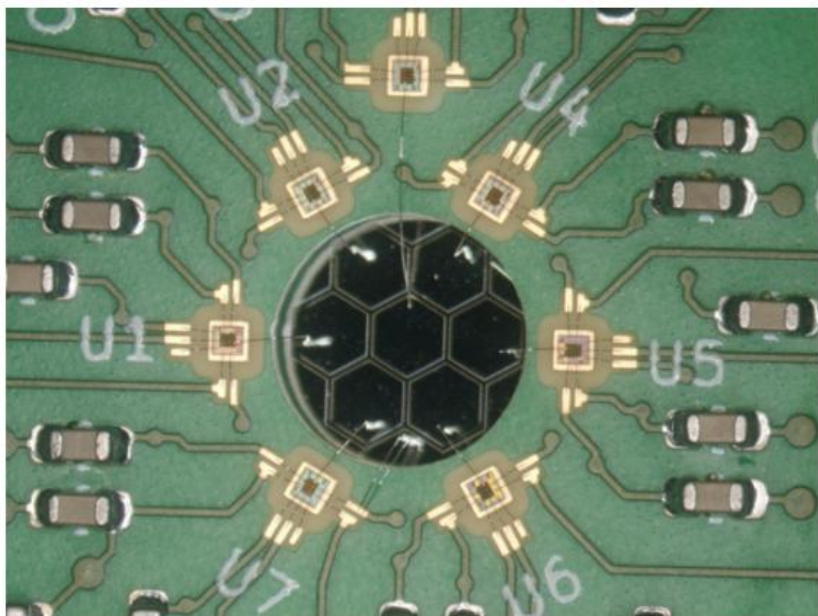


## X-ray Absorption Spectroscopy (XAS)

- The absorption coefficient of a chemical element is measured as a function of the scan in energy around the ionization threshold of an element.
- The XAS spectrum provides information on:
  - **A, B:** Electronic structure of the excited atom (oxidation state & environment)
  - **C:** Interatomic distance between the excited atom & its neighbours
  - **PP:** Oxidation state of the excited atom



*F.J. Iguaz et al., JINST 18 (2023) T06011*



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- 7 channel germanium sensor developed by BNL
- Good spectroscopy performance:
  - 218 eV at 5.9 keV at 0.5 us, 373 eV at 59.5 keV, limited by preamplifier.
  - Uniform pixel response