HEXITEC MHz

A Spectroscopic Imaging Camera with a 1 MHz Frame Rate Continuous Readout

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HEXITEC MHz

Funded by the: Centre for Instrumentation (CFI) run by Marcus French

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Detector Systems

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Agenda

1 HEXITEC vs HEXITEC$_{MHz}$

The next generation of HEXITEC systems

2 HEXITEC$_{MHz}$ Overview

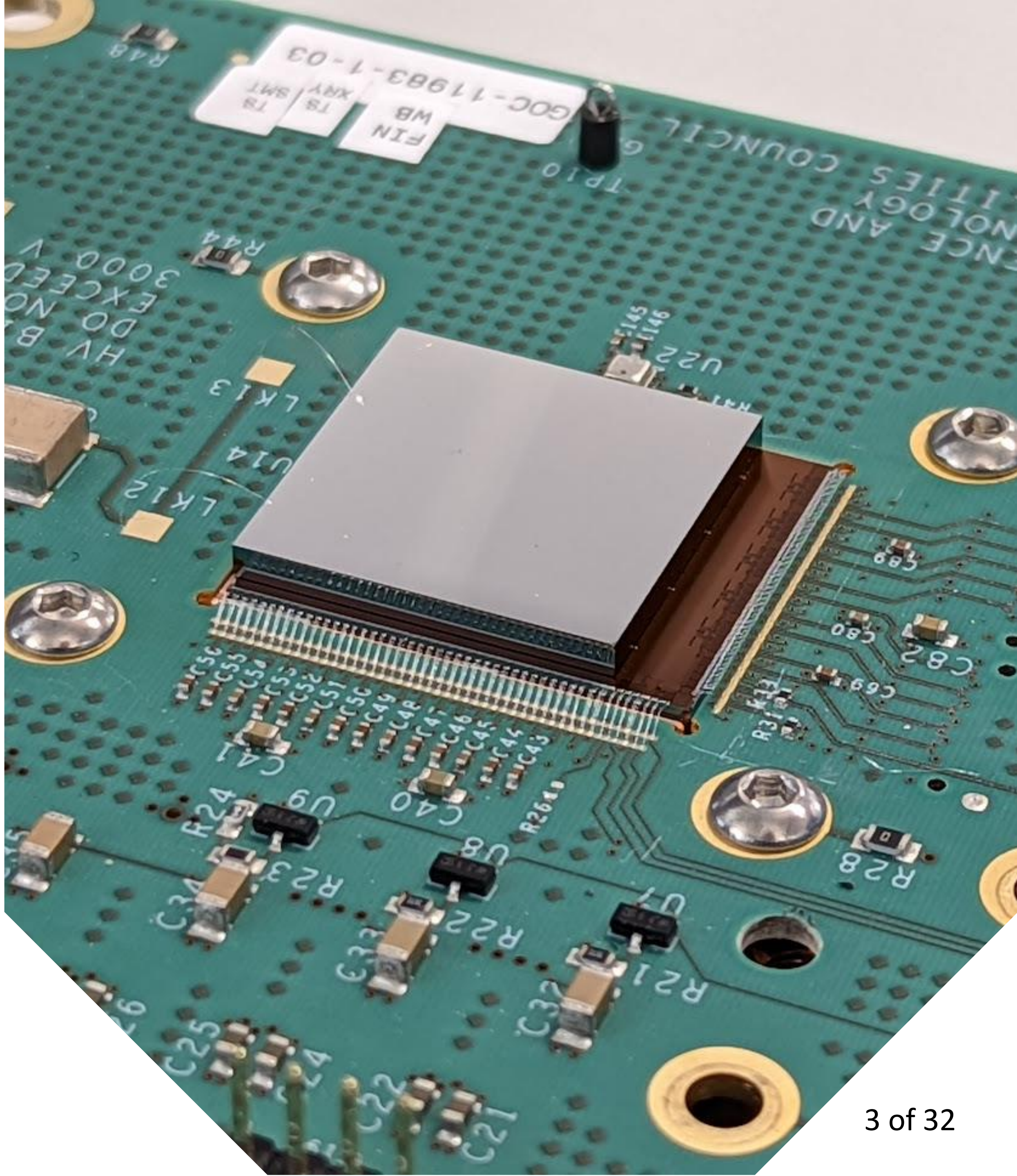
An introduction to our new HEXITEC$_{MHz}$ ASIC including its architecture and specification

3 Test Results

Characterisation of spectroscopic performance using a lab-based X-Ray source and Diamond Light Source synchrotron X-Rays

4 Next Steps

A look to the next 12 months



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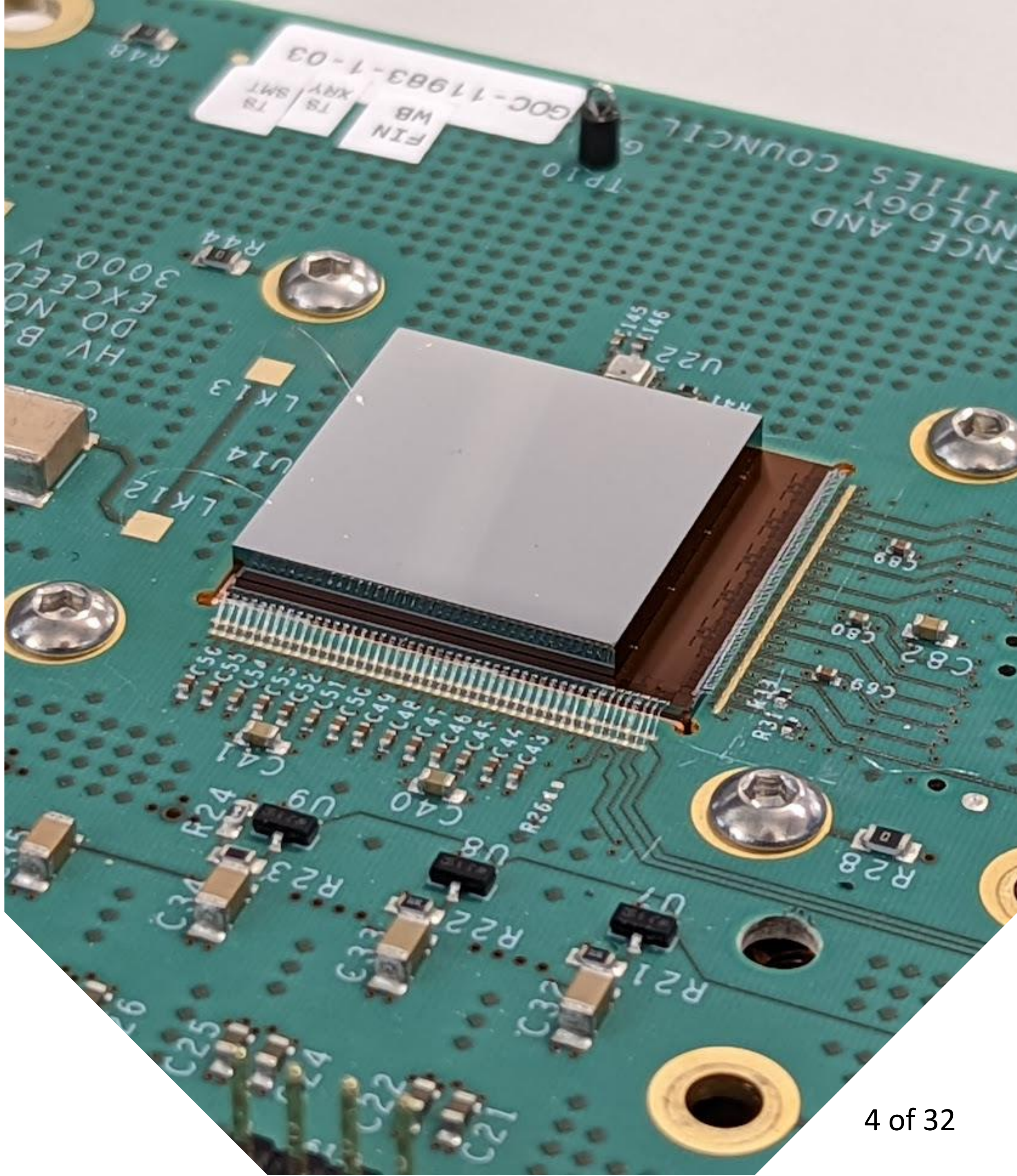
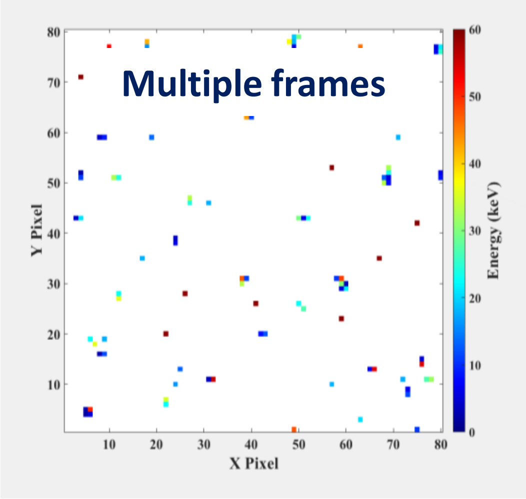
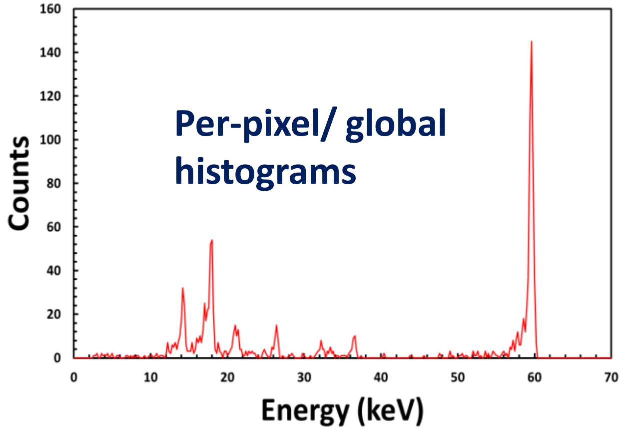


HEXITEC

HIGH ENERGY X-RAY IMAGING TECHNOLOGY

- **Fully spectroscopic X-Ray Imaging** with CdTe/ CdZnTe (CZT) detectors
- 80×80 pixel array on a 250 μm pitch
- **Analogue readout** via a rolling shutter to **4 ADCs in the DAQ**
- Maximum ~10 kHz data output (~100 MB s^{-1})
- AMS 0.35 μm - since 2010





HEXITEC specifications

Parameter	HEXITEC
Pixel Pitch (μm)	250
Array Size	80×80
Max Frame Rate (kHz)	~10
Max Spectroscopic Flux (ph s^{-1} mm^{-2})	~10^4
Digitisation	Off-chip
Detector Type	Peak Track + Hold
Gain stages (keV in CZT)	200
	600
FWHM$_{@100keV}$ (keV in CZT)	< 1 • HF-CZT: 0.79 keV @ 59.54 keV [1] • 300-μm thick p-type Si: 0.59 keV @ 59.54 keV [2]

[1] DOI: 10.3390/s20102747 [2] DOI: 10.1088/1748-0221/17/05/P05030

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- HEXITEC has been used across many applications including:

Compton X-Ray Imaging [3]

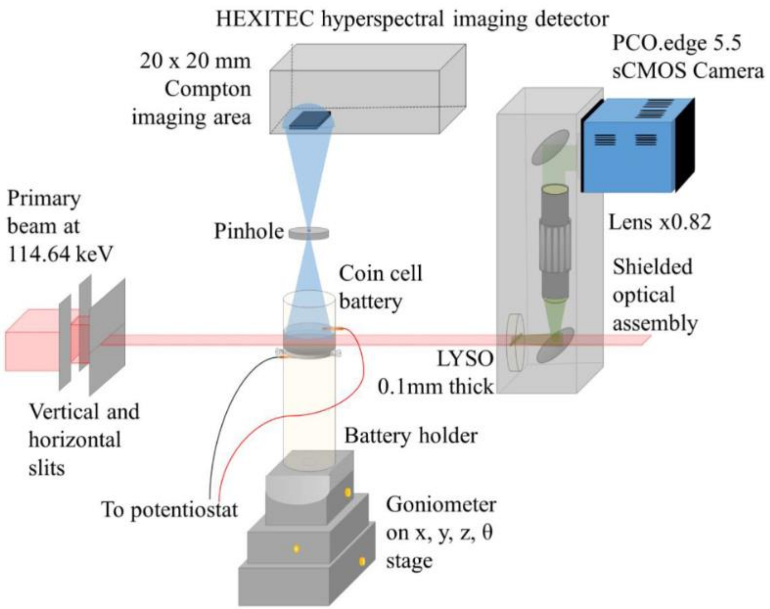

Figure 1. Schematic of the correlative X-Ray Compton scattering imaging (XCS-I) and X-Ray computed tomography (XCT) technique experimental set-up

X-Ray Fluorescence Imaging [4]

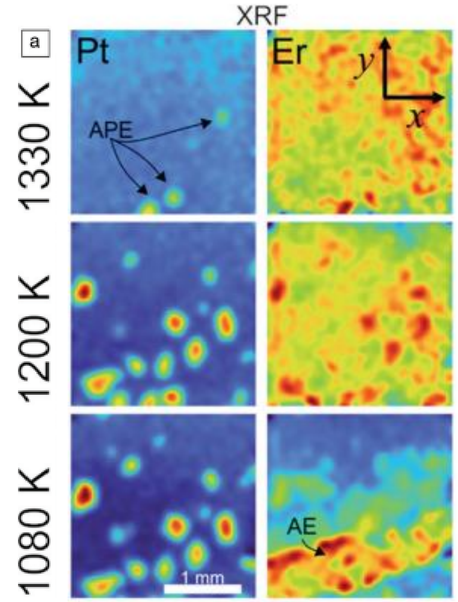

Figure 7. (a) Pt and Er XRF intensity maps as a function of temperature during the solidification of an Al-23Pt-20Er alloy at 0.1 Ks^{-1}.

Hyperspectral X-Ray Tomography [5]

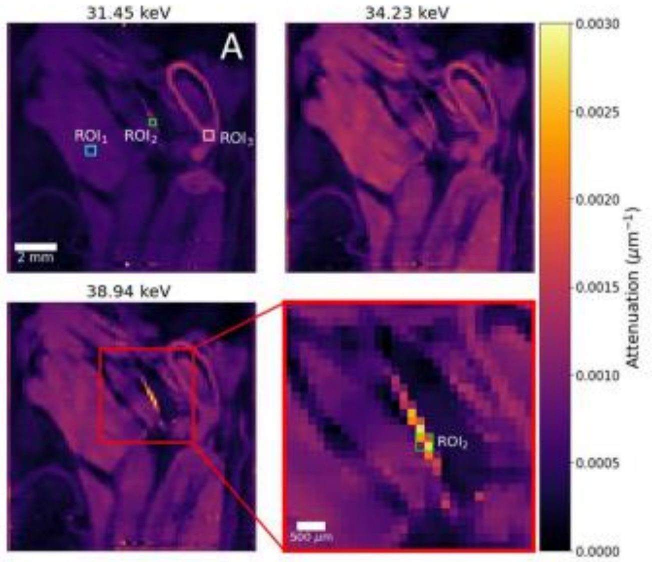

Figure 2. Voxel spectra analysis for double-stained hindlimb specimen. (A) Single image slice in the sagittal plane across three monochromatic energy channels, following iterative reconstruction. A set of three regions-of-interest (ROIs) are highlighted for voxel spectra analysis.

[3] DOI: 10.1016/j.mtener.2022.101224 **[4]** DOI: 10.1557/mrs.2020.270 **[5]** DOI: 10.1038/s41598-022-23592-0

HEXITEC
HIGH ENERGY X-RAY IMAGING TECHNOLOGY

BUT …

- **HEXITEC is frame-rate and therefore flux limited**
    - Charge-sharing corrections require <10% frame occupancy
    - This limits spectroscopic imaging @10 kHz to a **max X-Ray flux of ~10^4 ph s^{-1} mm^{-2}**

→ There is a need for a continuous spectroscopic X-Ray detector that operates at faster frame rates

- **Faster (MHz) imaging requires**:
    - In-pixel digitisation
    - High-speed serialisers
    - Dedicated FPGA processing

- These **requirements apply to a large number of STFC's upcoming detector development projects**
    - E.g. DynamiX, C100

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HEXITEC$_{MHz}$

A new fully spectroscopic X-Ray imaging detector:

- 80×80 pixels on a 250 μm pitch
- New front-end design – now an **integrating** detector
- **On-chip 12-bit digitisation** (no external ADCs)
    - Data outputted via **20 × 4.1 Gbps serialisers**
- **1 MHz continuous frame rate**
    - Spectroscopic X-Ray fluxes of **>10^6 ph s^{-1} mm^{-2}**

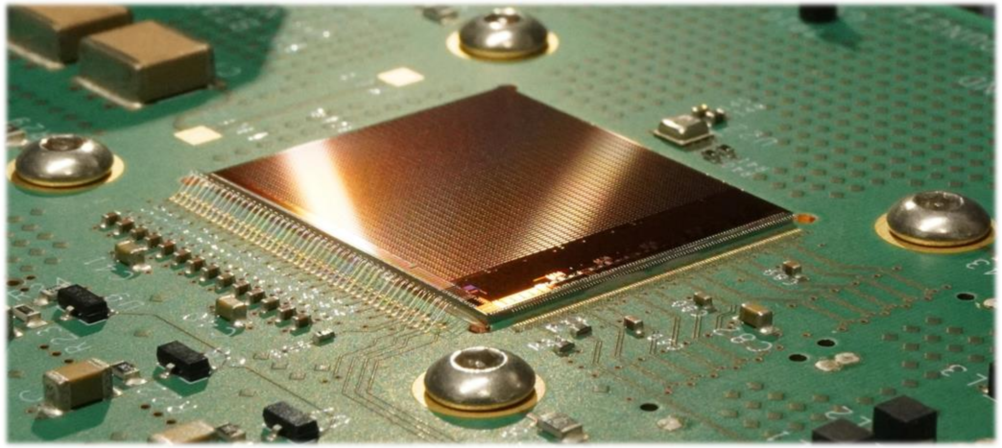

Photo of ASIC

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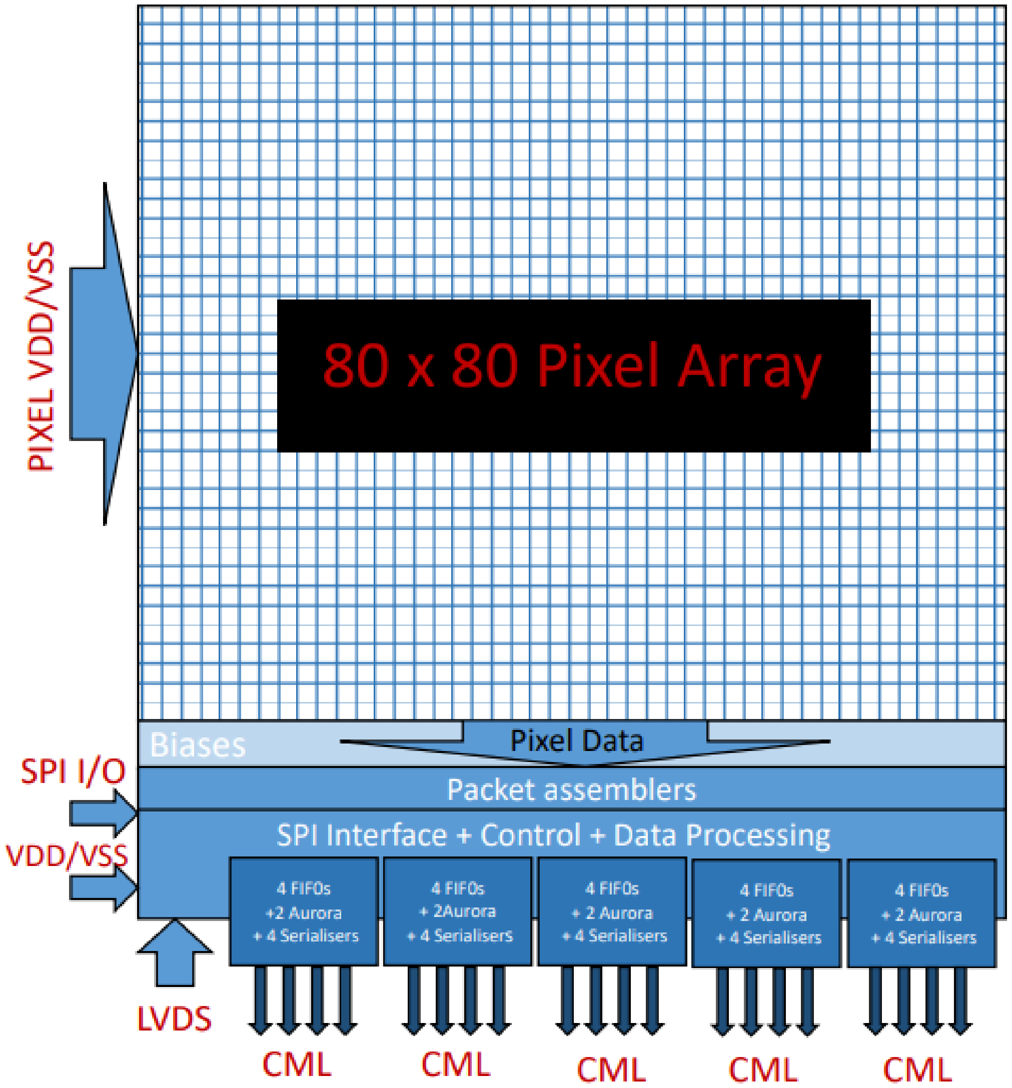
Comparison of HEXITEC and HEXITEC$_{MHz}$ specifications

Parameter	HEXITEC	HEXITEC$_{MHz}$
Pixel Pitch (μm)	250	250
Array Size	80×80	80×80
Max Frame Rate (kHz)	~10	**1000**
Max Spectroscopic Flux (ph s^{-1} mm^{-2})	~10^4	**>10^6**
Digitisation	Off-chip	**On-chip**
Detector Type	Track + Hold	**Integrating**
Gain stages (keV in CZT)	200	100
	600	200
		300
FWHM@100keV (keV in CZT)	< 1	< 1
Power Consumption (W)	1.5	15

HEXITEC MHz



ASIC block diagram

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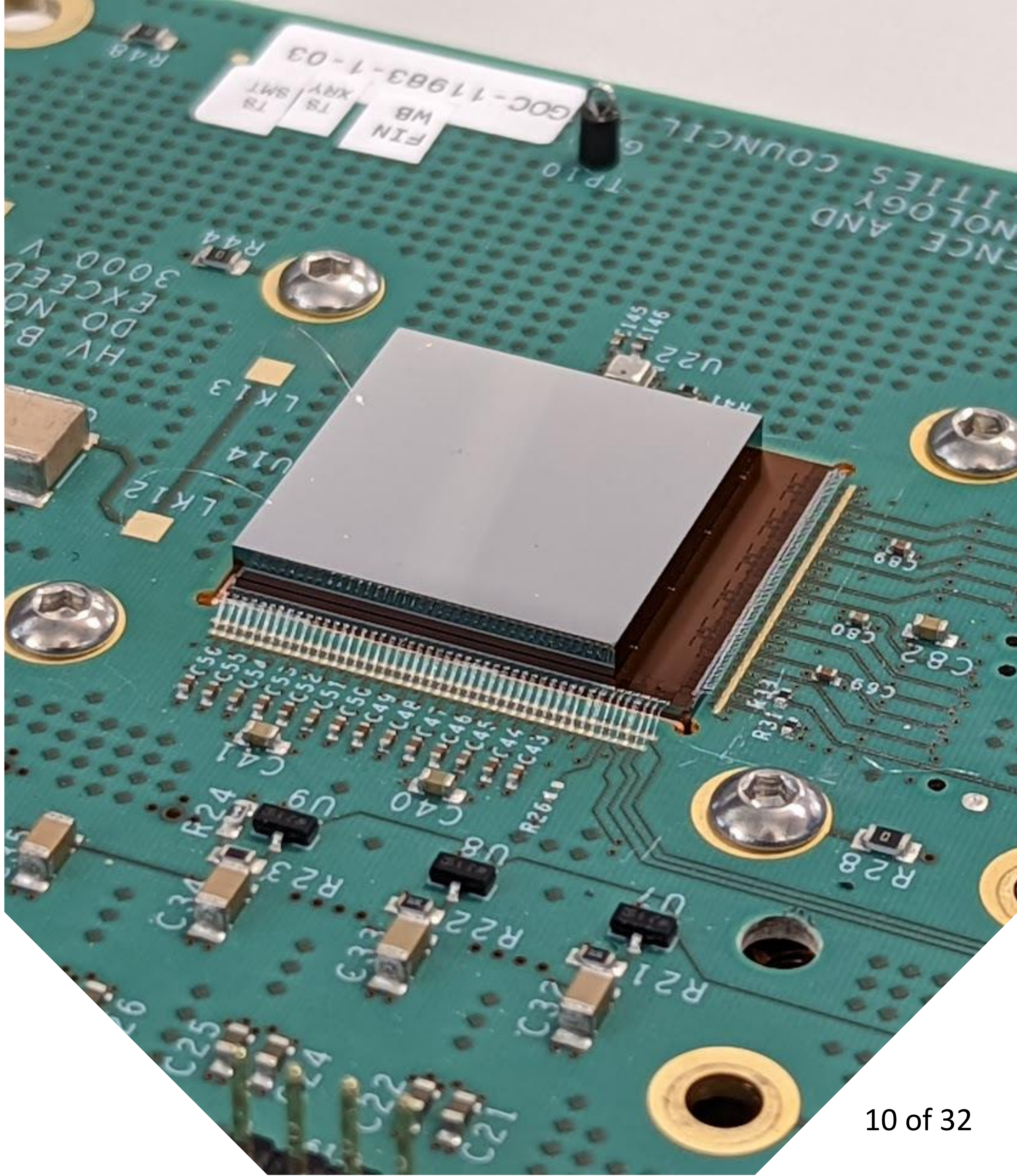
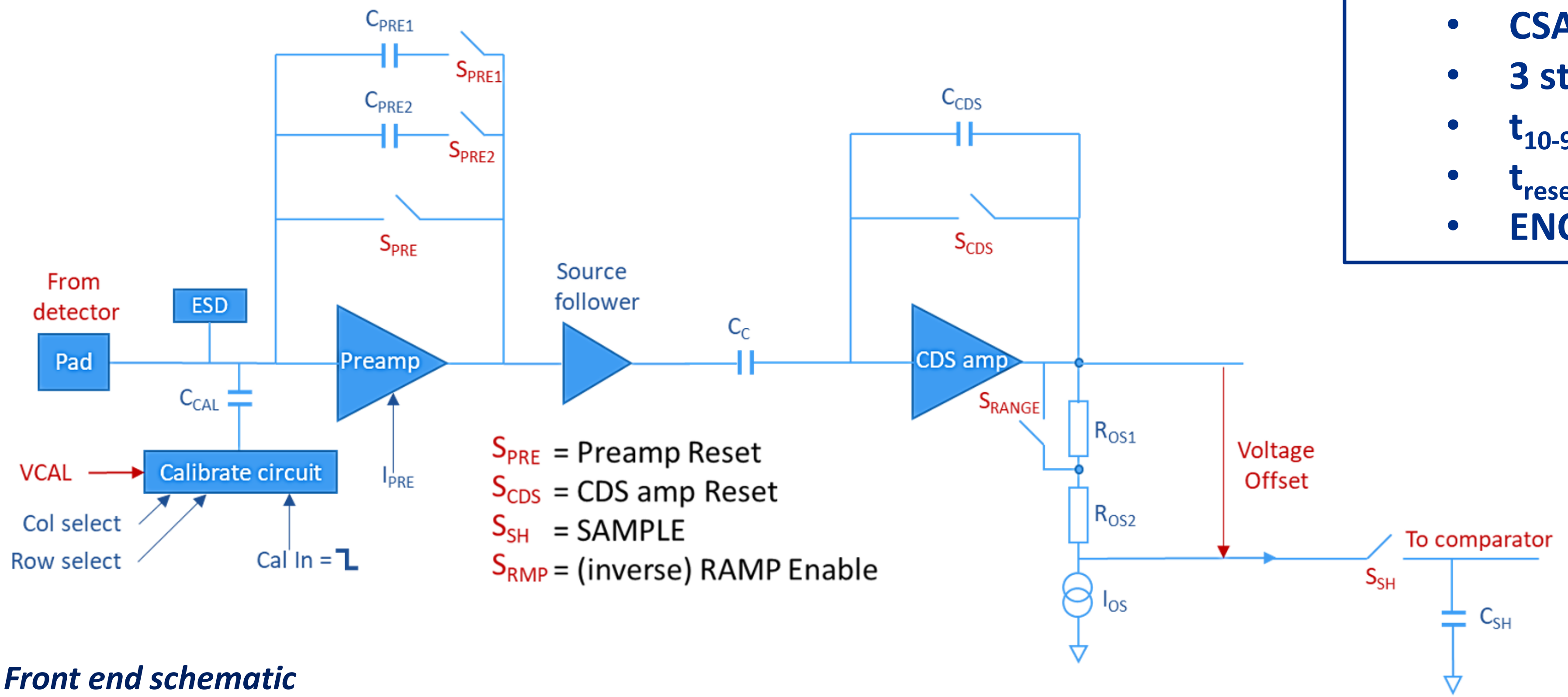


HEXITEC$_{MHz}$ - Integrating Front End



S_{PRE} = Preamp Reset
S_{CDS} = CDS amp Reset
S_{SH} = SAMPLE
S_{RMP} = (inverse) RAMP Enable

Front end schematic

Properties:
- CSA + CDS amplifier
- 3 static dynamic ranges
- t_{10-90} = 50 ns
- t_{reset} ≈ 90 ns
- ENC < 60e^-

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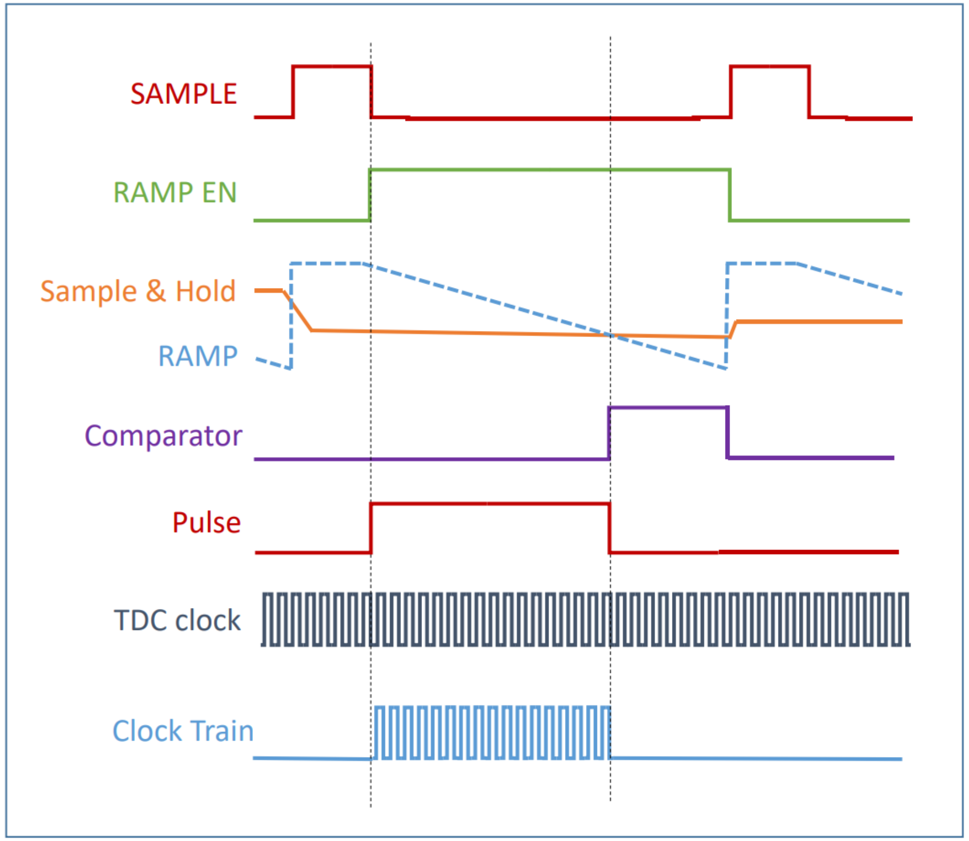
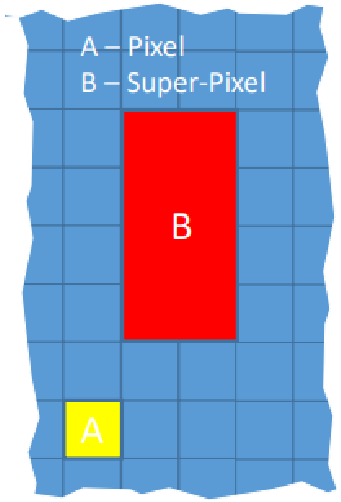
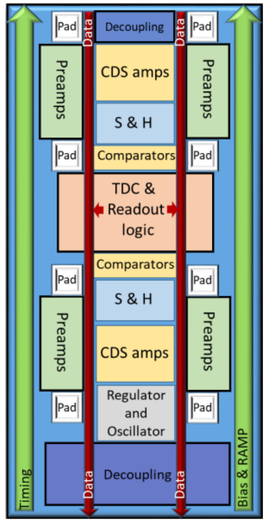
HEXITEC$_{MHz}$ - In-Pixel TDC



TDC signal timing

- **12-bit** digitisation
  - **The Sample & Hold signal is compared with a ramp with a programmable slew**
- The ASIC comprises **800 super-pixels of 2×4 pixels**
  - These contain **one TDC block and shared readout logic**





Super-pixel schematics

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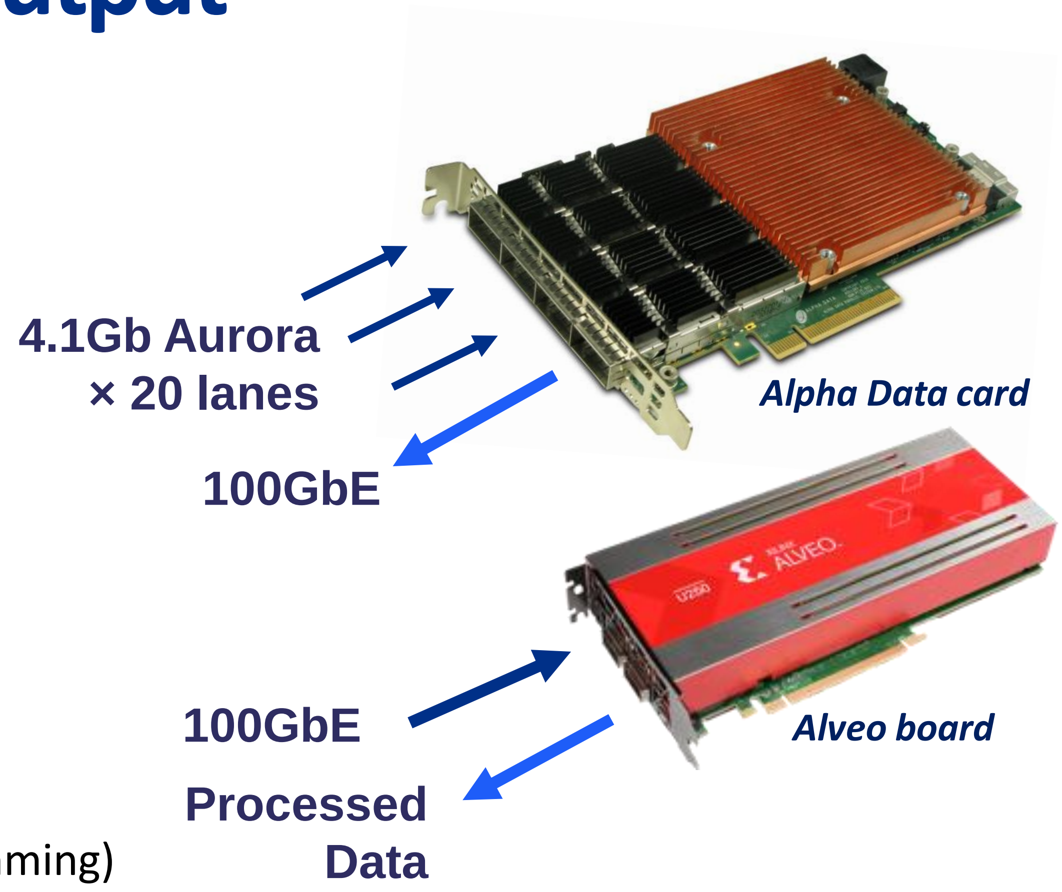
HEXITEC$_{MHz}$ - Data Output

- 80×80 array is divided into **divisions of 4 columns**
  - Each division has **packet-assembler** and dedicated **serialiser**
  - Packets constructed using **Xilinx's Aurora 64B/66B protocol**
  - Serialisers operate at **4.1 Gb s^{-1} (total data rate ≈ 10 GBs^{-1})**

What to do with all this data?

- Two receiving data planes:
  - **First-stage FPGA – Alpha Data card**
    - Recovers and reorders the received optical data
  - **Second-stage FPGA – Xilinx Alveo U50 board**
    - Data corrections (darks, energy calibration)
    - Data reduction (charge-sharing discrimination, histogramming)



- Then received by **ODIN Data, a scalable data-processing and acquisition network**

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HEXITEC$_{MHz}$ - Data Output

- 80×80 array is di
    - Each divisio
    - Packets cor
    - Serialisers c

What to do with a

- Two receiving da
    - **First-stage**
        - Recove
    - **Second-sta**
        - Data c
        - Data red

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Journal of Instrumentation

PAPER • OPEN ACCESS

Spectroscopic X-ray imaging at MHz frame rates — the HEXITEC$_{MHz}$ ASIC

L. Jones[2,1], S. Bell[1], B. Cline[1], T. Gardiner[1], M. Hart[1], M. Prydderch[1], P. Seller[1], M. Veale[1] and M. Wilson[1]

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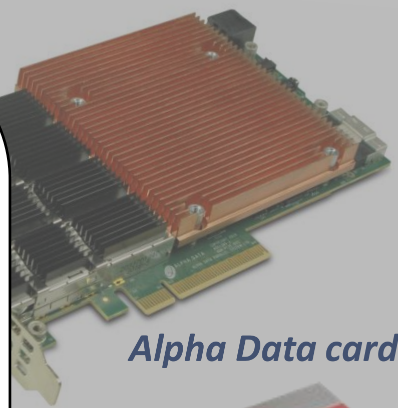

Alpha Data card

Alveo board

- Then received by **ODIN Data, a scalable data-processing and acquisition network**

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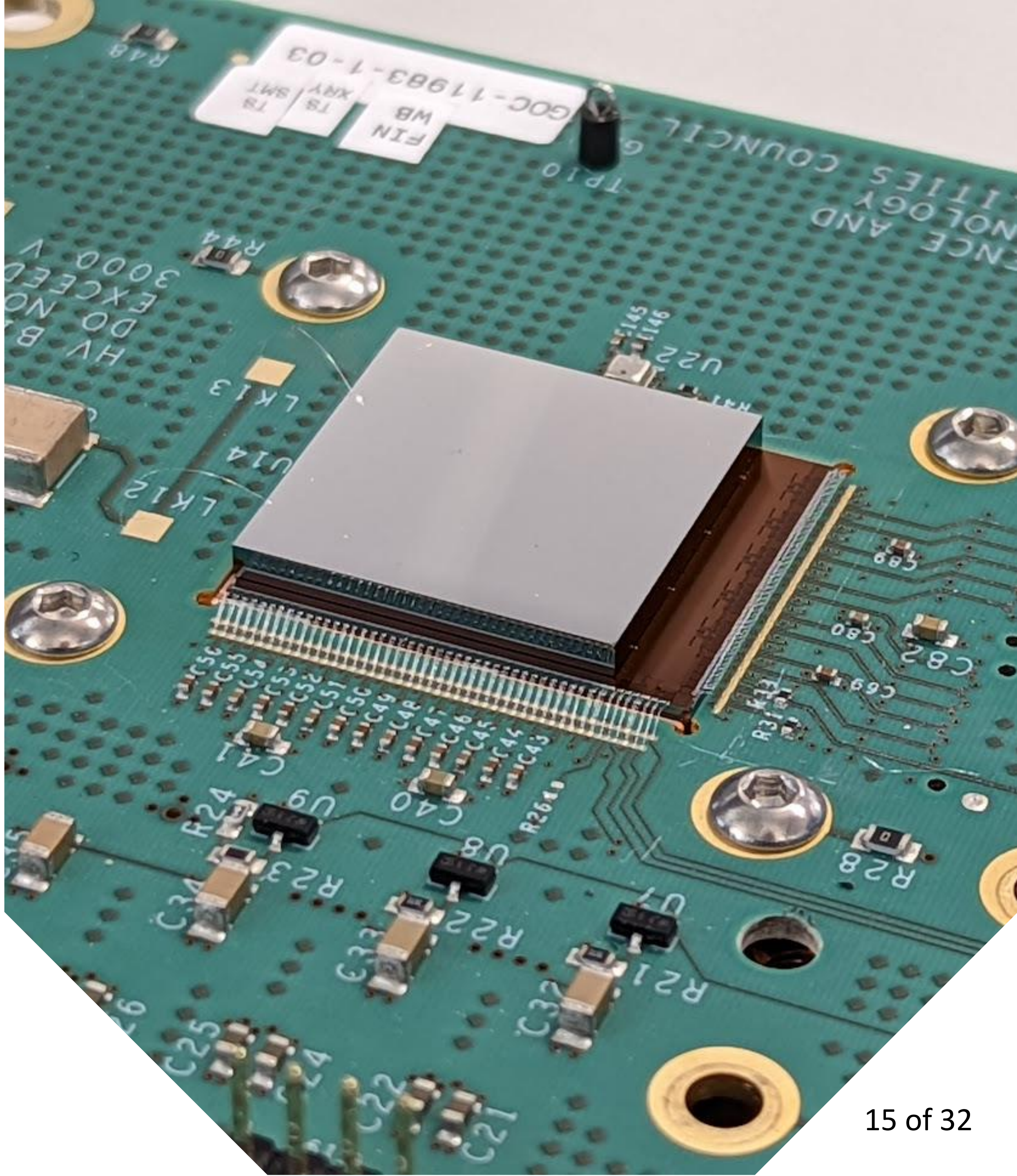
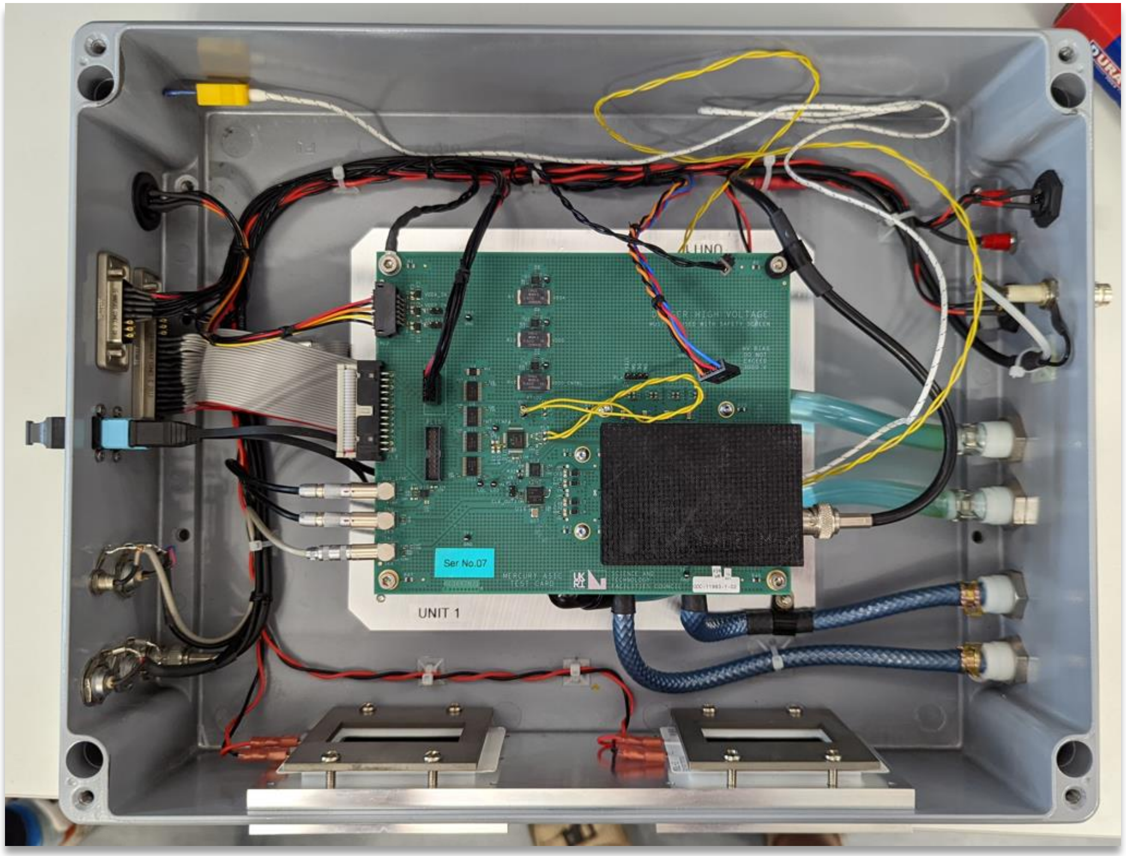


Current Status

50 cm

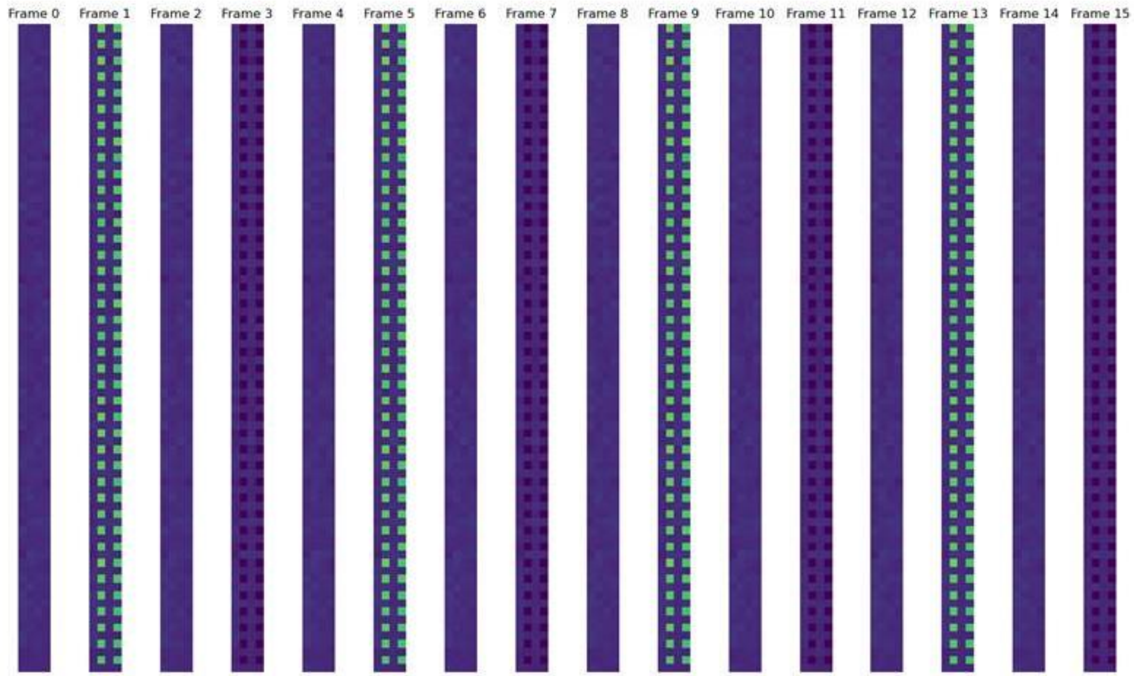


30 cm

HEXITEC$_{MHz}$ test enclosure

- ASIC is fully functioning
- Using **test enclosure**
- FPGA firmware in development – at present, **1 channel (4×80 pixels) over fast data**

15 μs



1 μs

Fast data output

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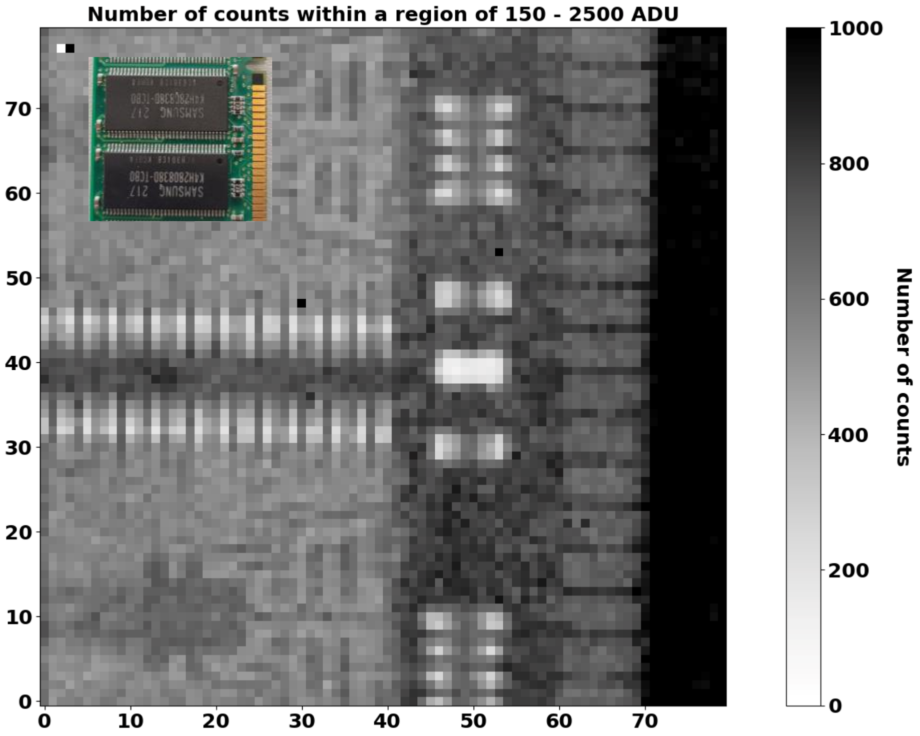
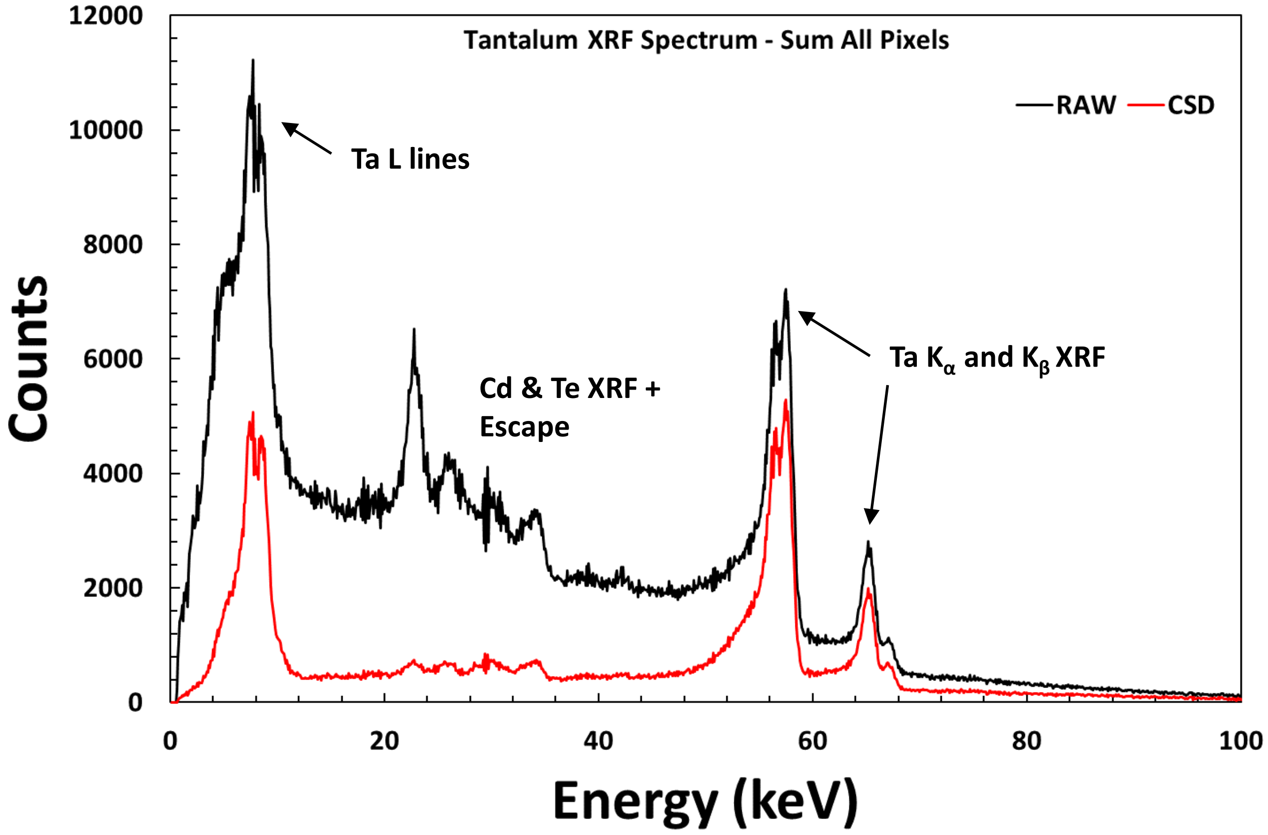
Testing – Initial X-Ray Tests



X-Ray transmission measurements of a DDR Ram Card using a HEXITEC$_{MHz}$ HF-CZT sensor



X-Ray Fluorescence (XRF) measurements of Ta foil using a HEXITEC$_{MHz}$ HF-CZT sensor in medium-gain mode

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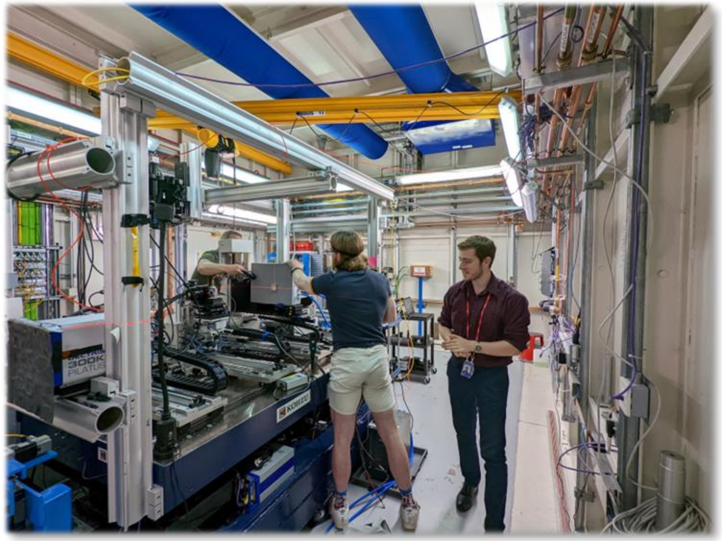
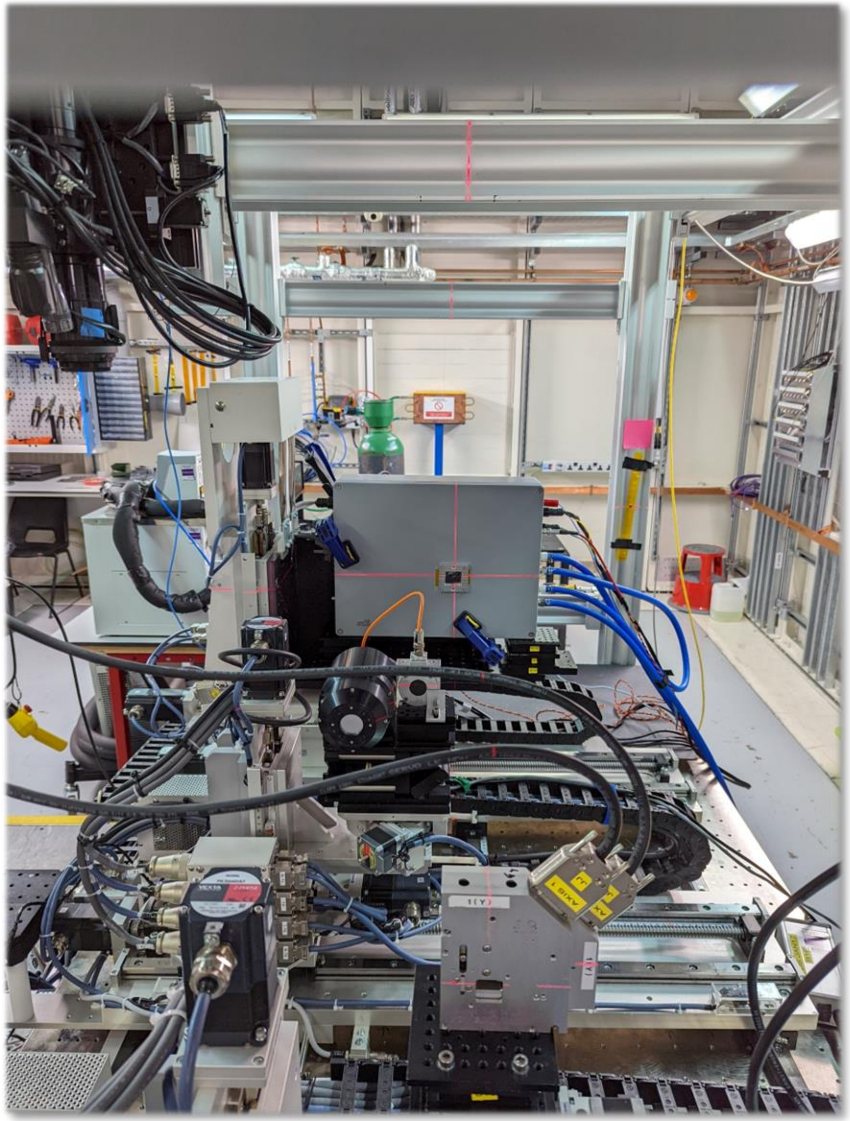
Experimentation at diamond

- **B16 Beamline: August and December 2022**
  - Monochromatic X-Rays: 10 – 20 keV
  - Photon fluxes: **10^5 – 10^8 ph s^{-1} mm^{-2}**
  - 1 MHz data stream on one fast-data channel
  - Tested **p-type Si (300 µm)**, **HF-CZT (2 mm), GaAs (500 µm)** devices

- Beamline scientists: Vishal Dhamgaye, Oliver Fox, Kawal Sawhney

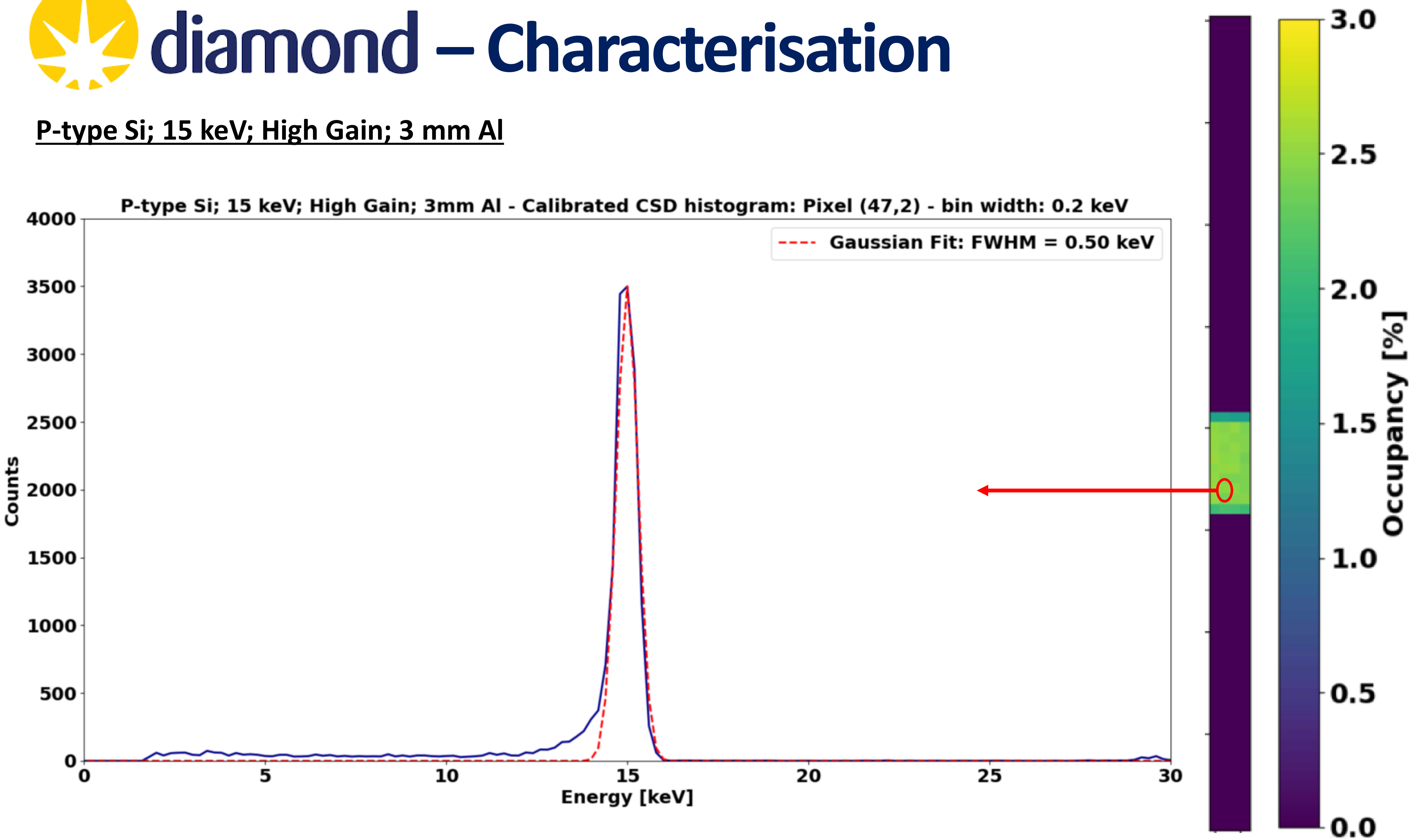




B16 setup photos

diamond – Characterisation

P-type Si; 15 keV; High Gain; 3 mm Al



Occupancy across fast-data channel

diamond – Characterisation

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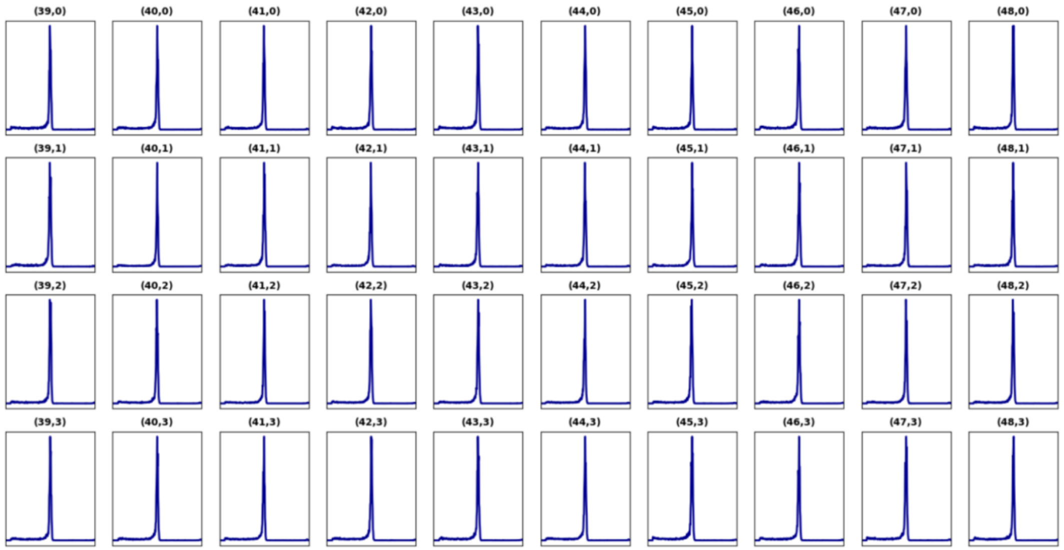
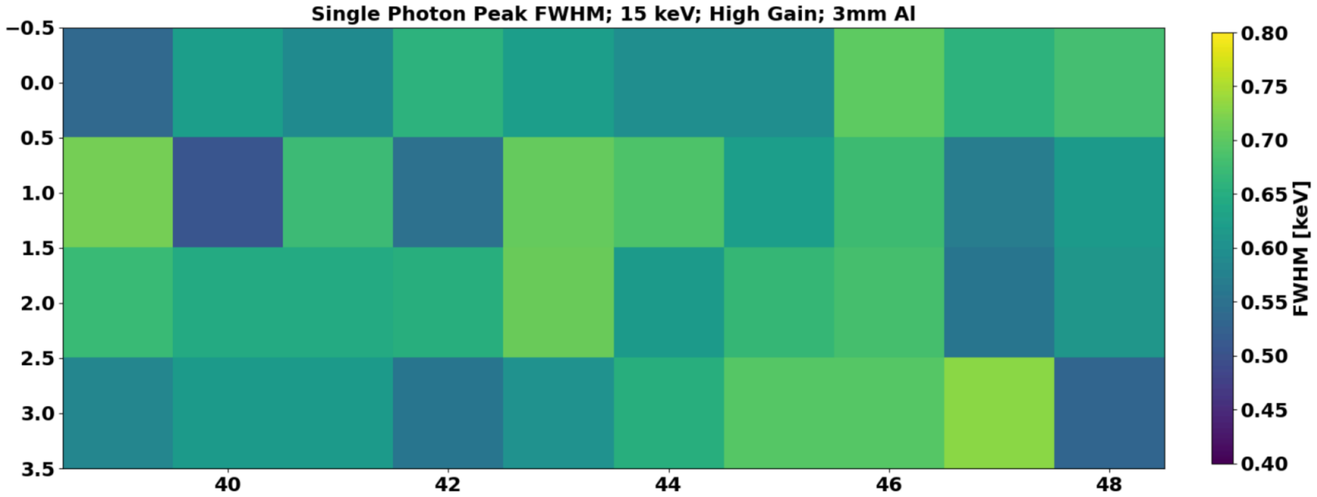
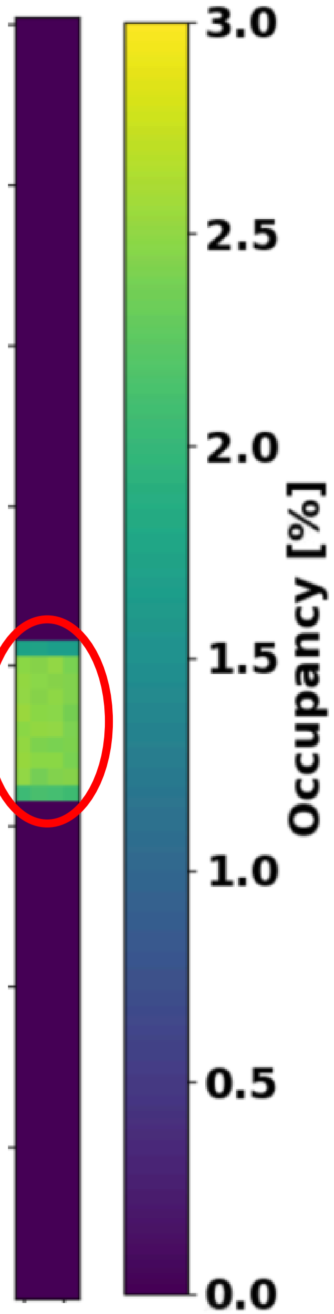


Calibrated histograms in beam area

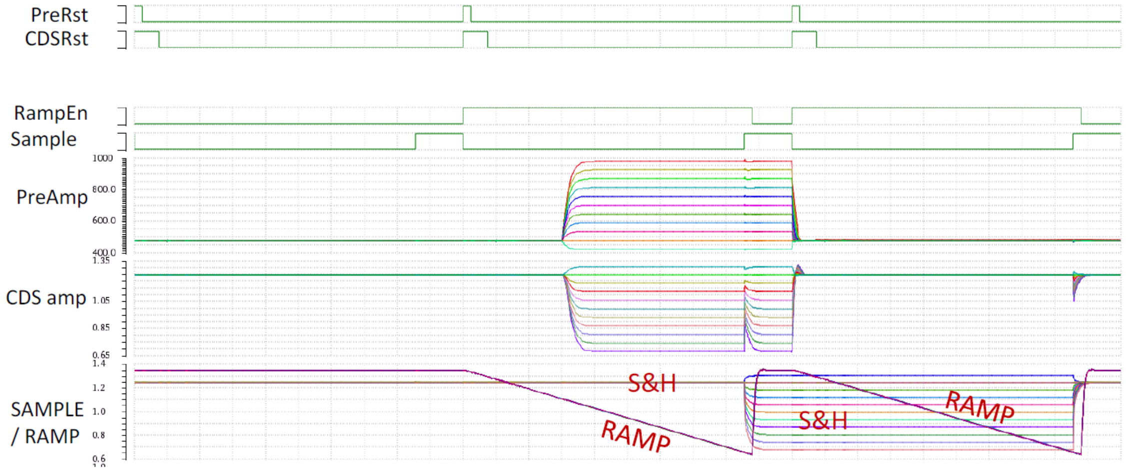


Single photon FWHM in beam area

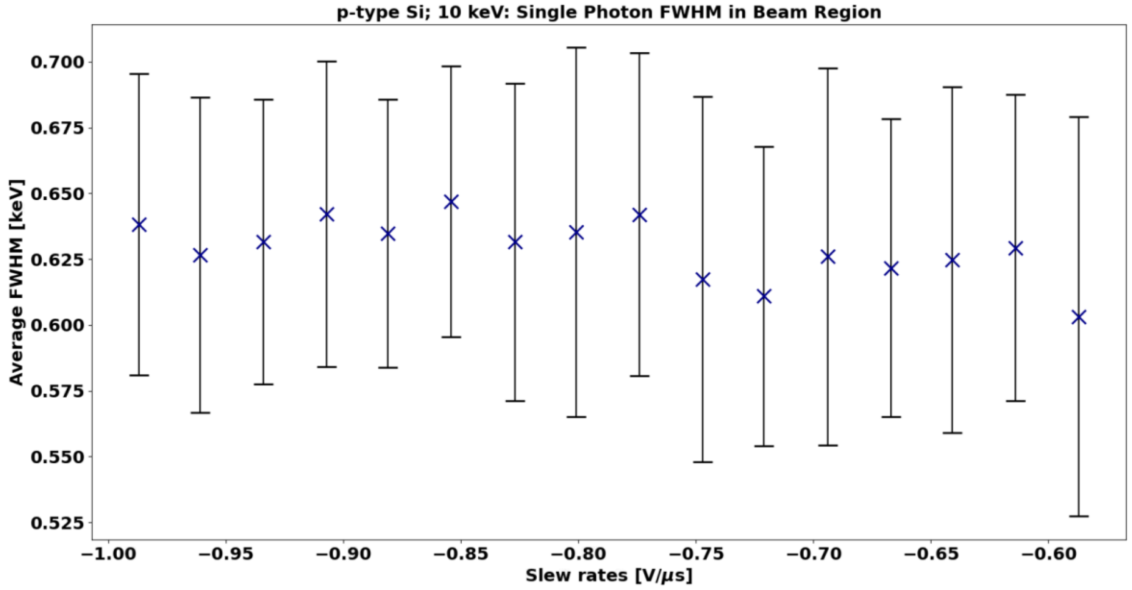


Occupancy across fast-data channel

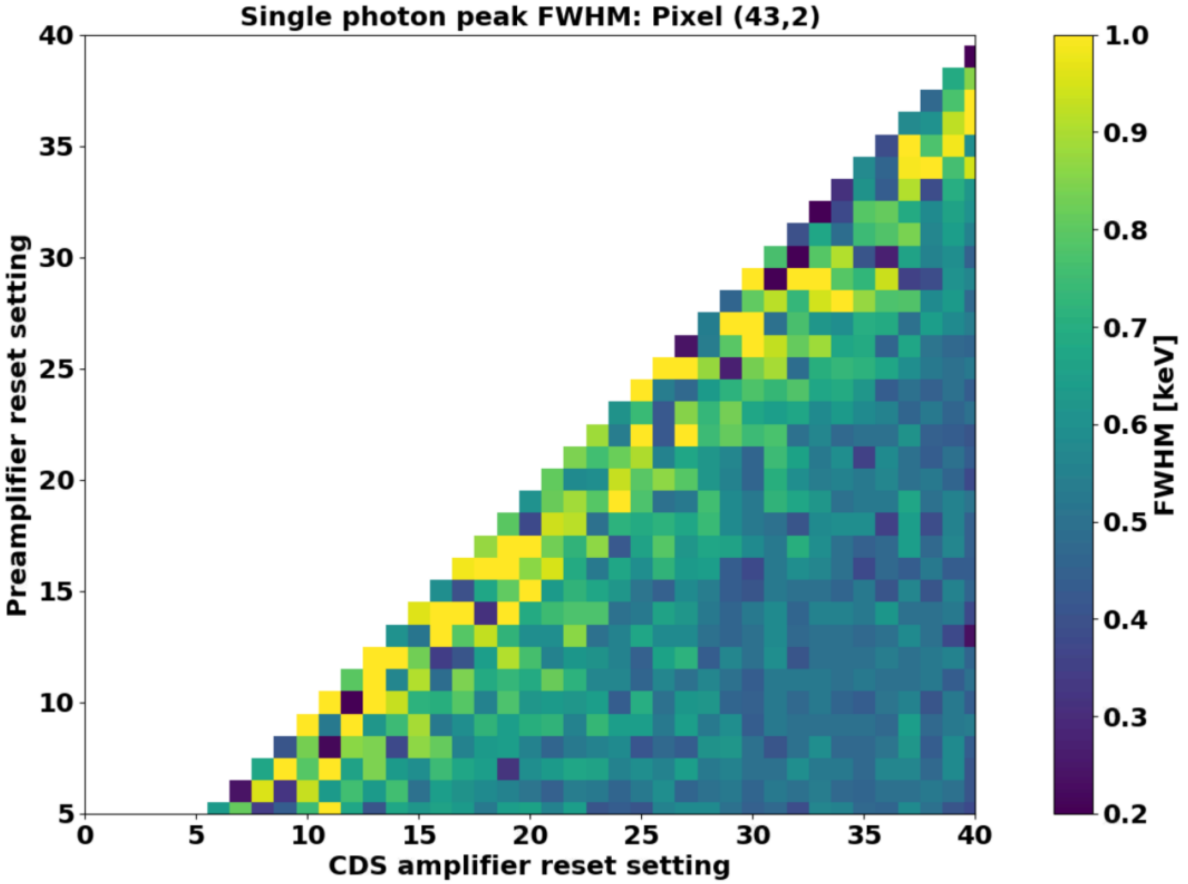
diamond – Optimisation



Timing signals schematic



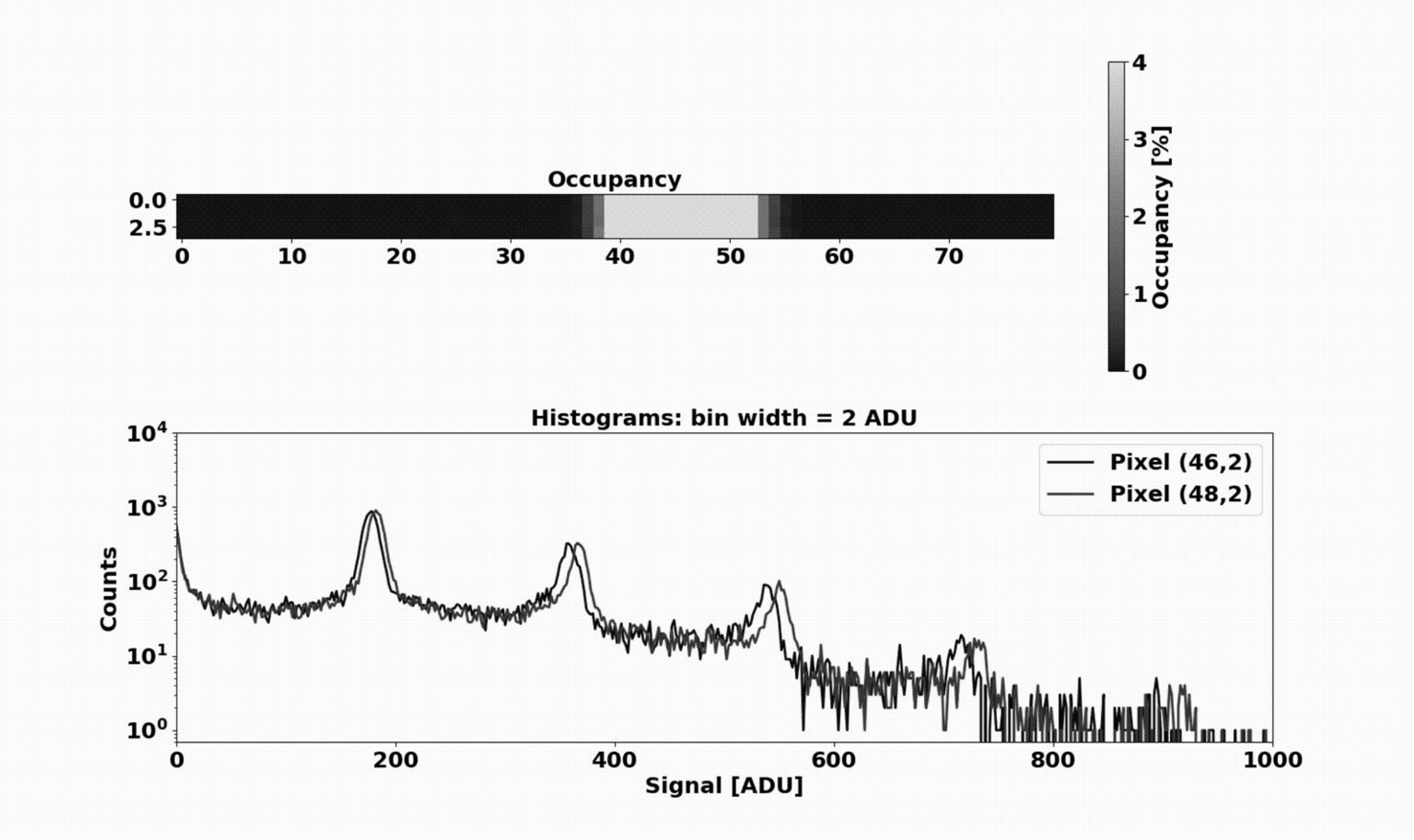
Optimising ramp slew rate



Optimising preamplifier and CDS amplifier timings

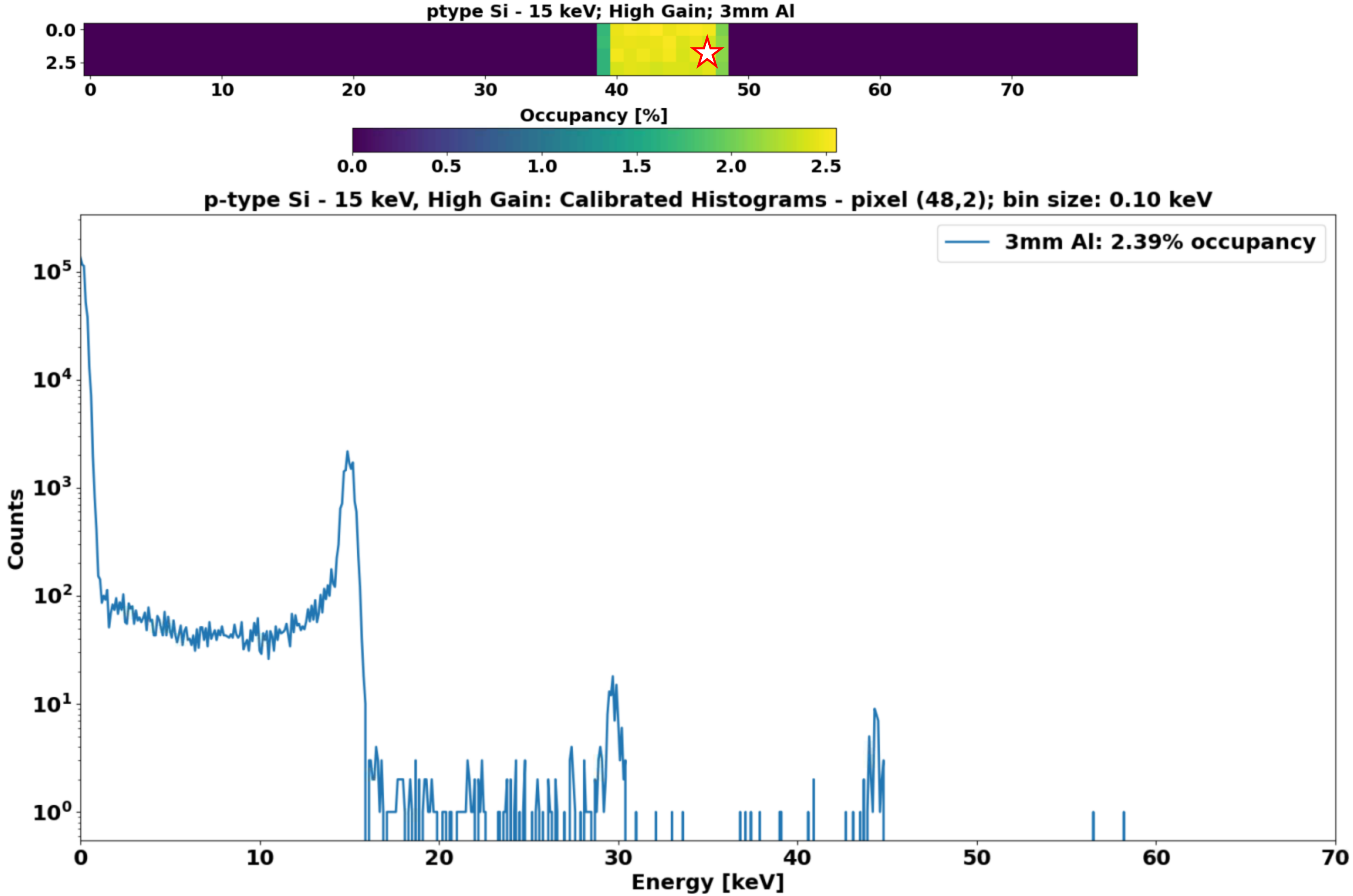
diamond – Dynamic Measurements

P-type Si: Changing slit size over 60 seconds (30 ms/video frame)



diamond – Integrating Measurements

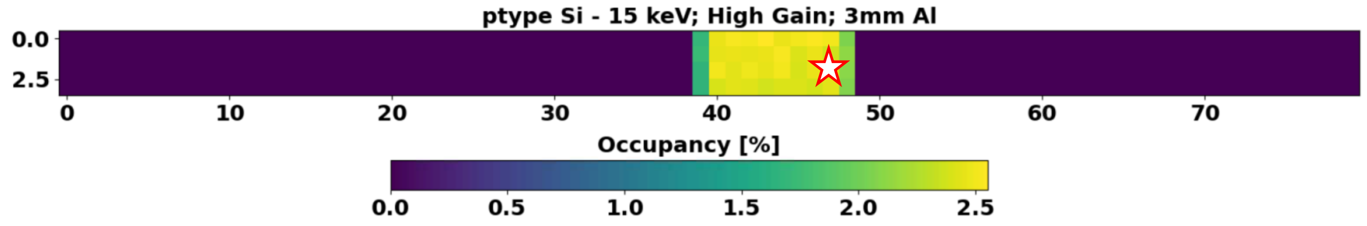
<u>P-type Si; 15 keV; High Gain; 3 mm Al – 0 mm Al</u>

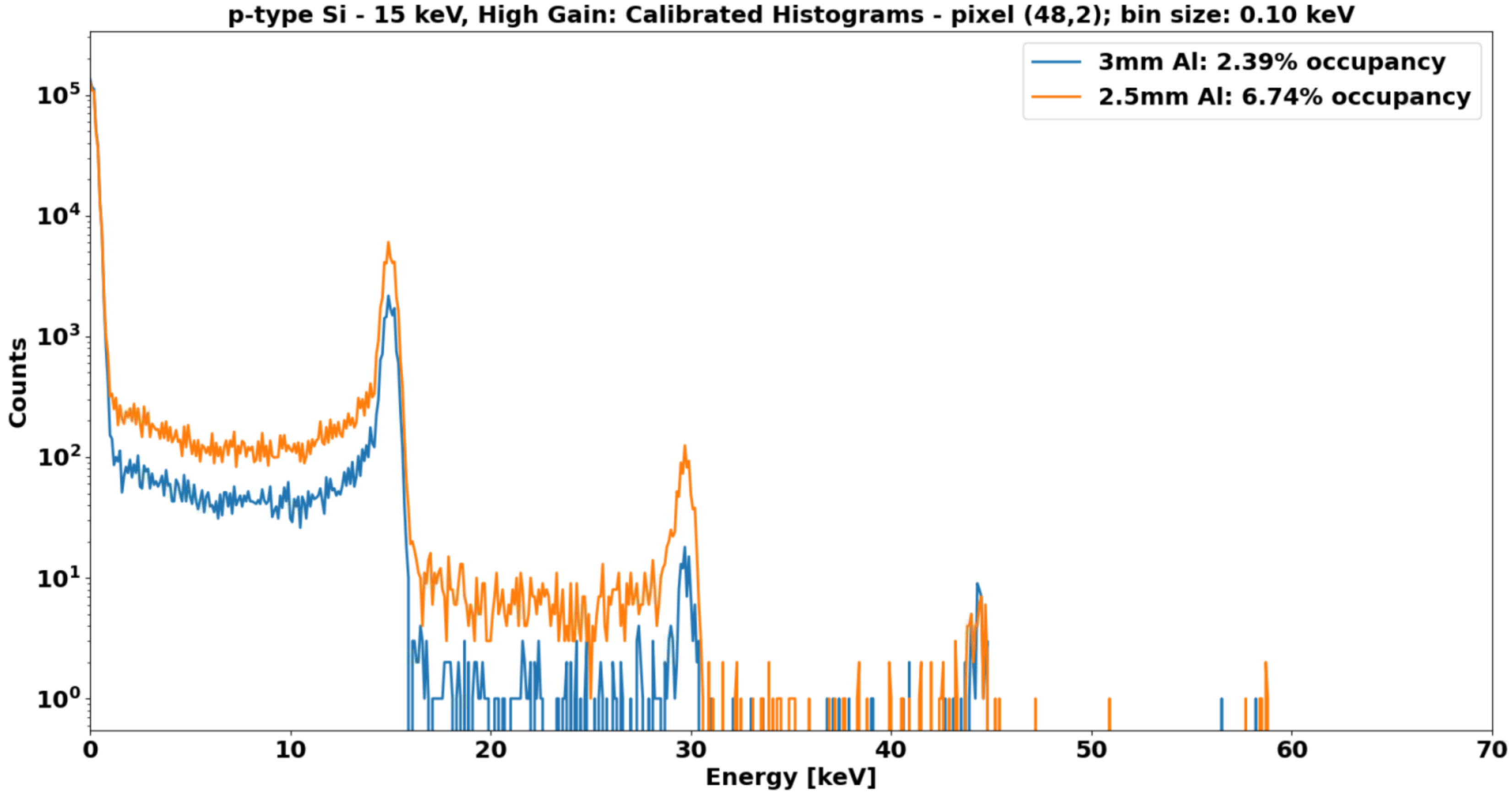


Calibrated histograms of pixel (48,2)

diamond – Integrating Measurements

P-type Si; 15 keV; High Gain; 3 mm Al – 0 mm Al





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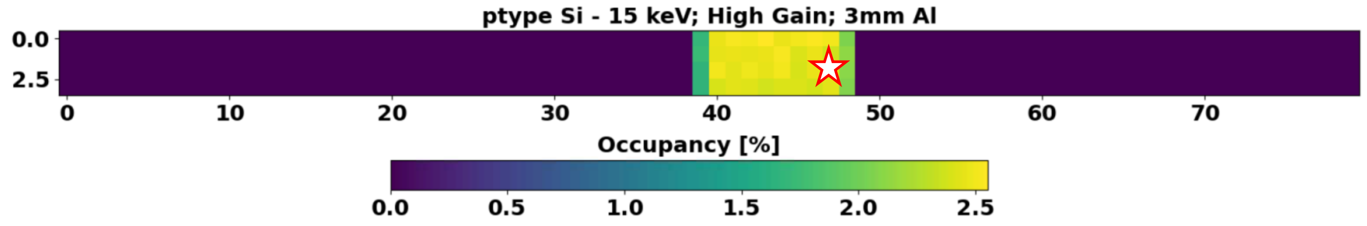

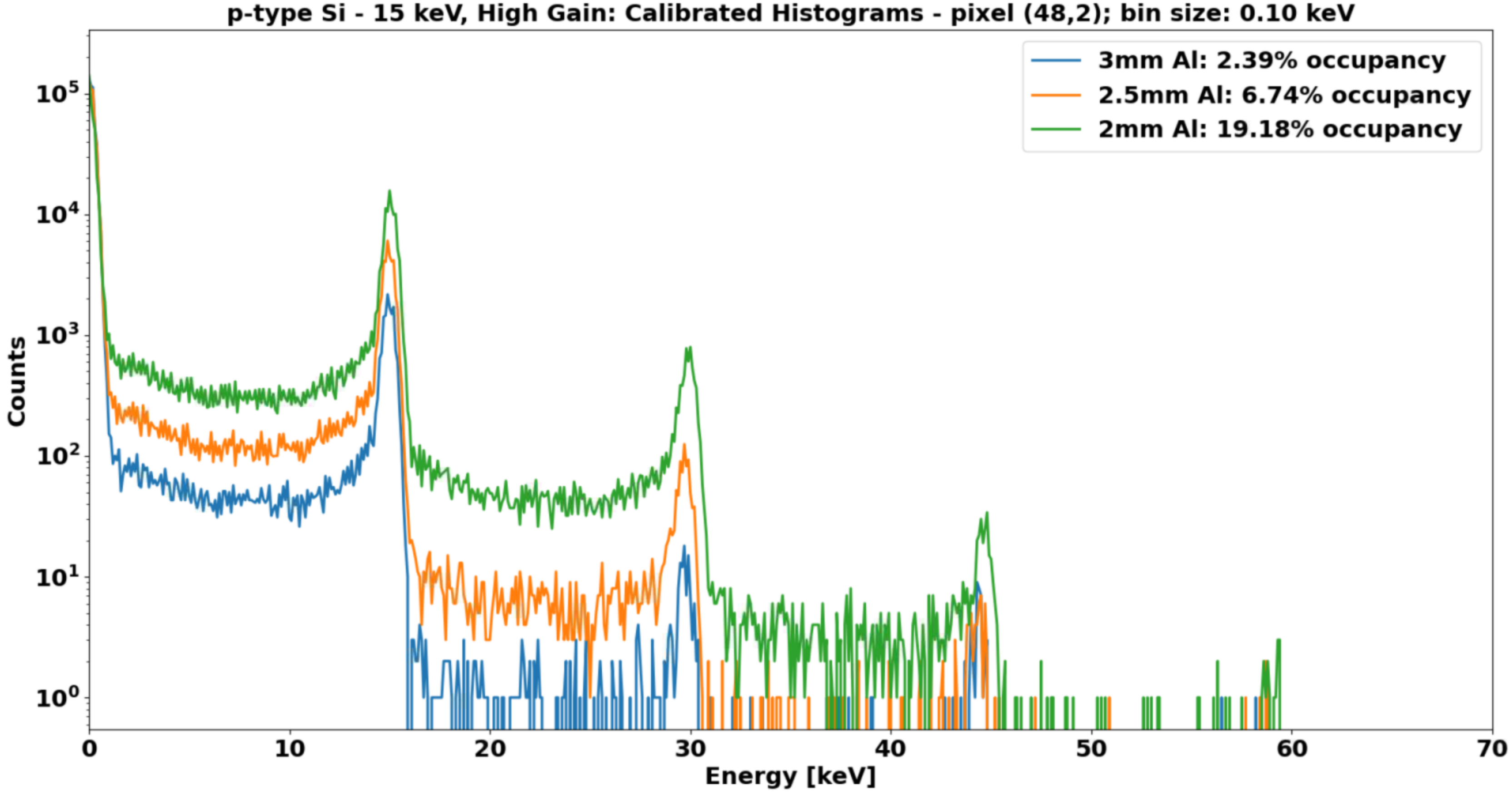

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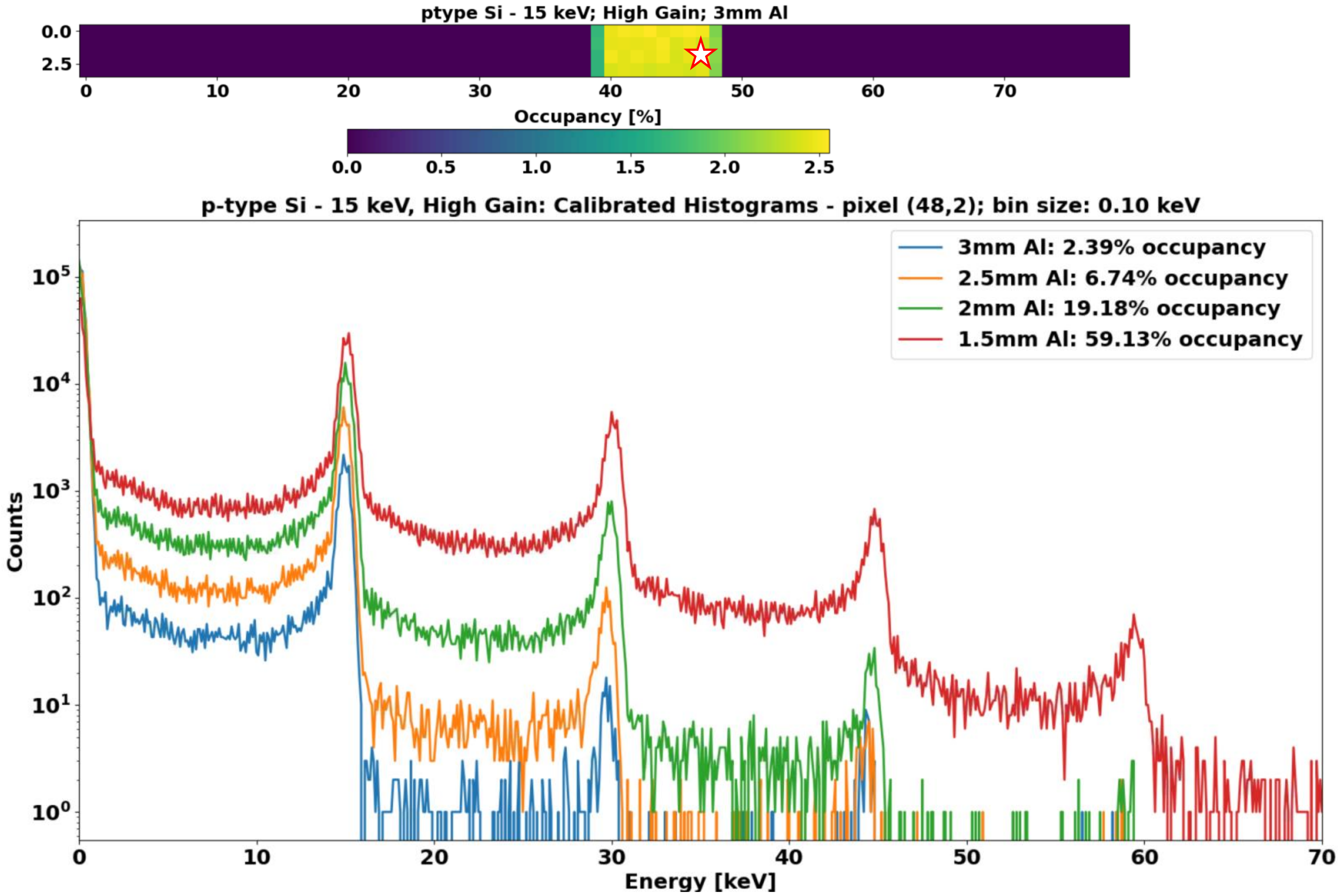

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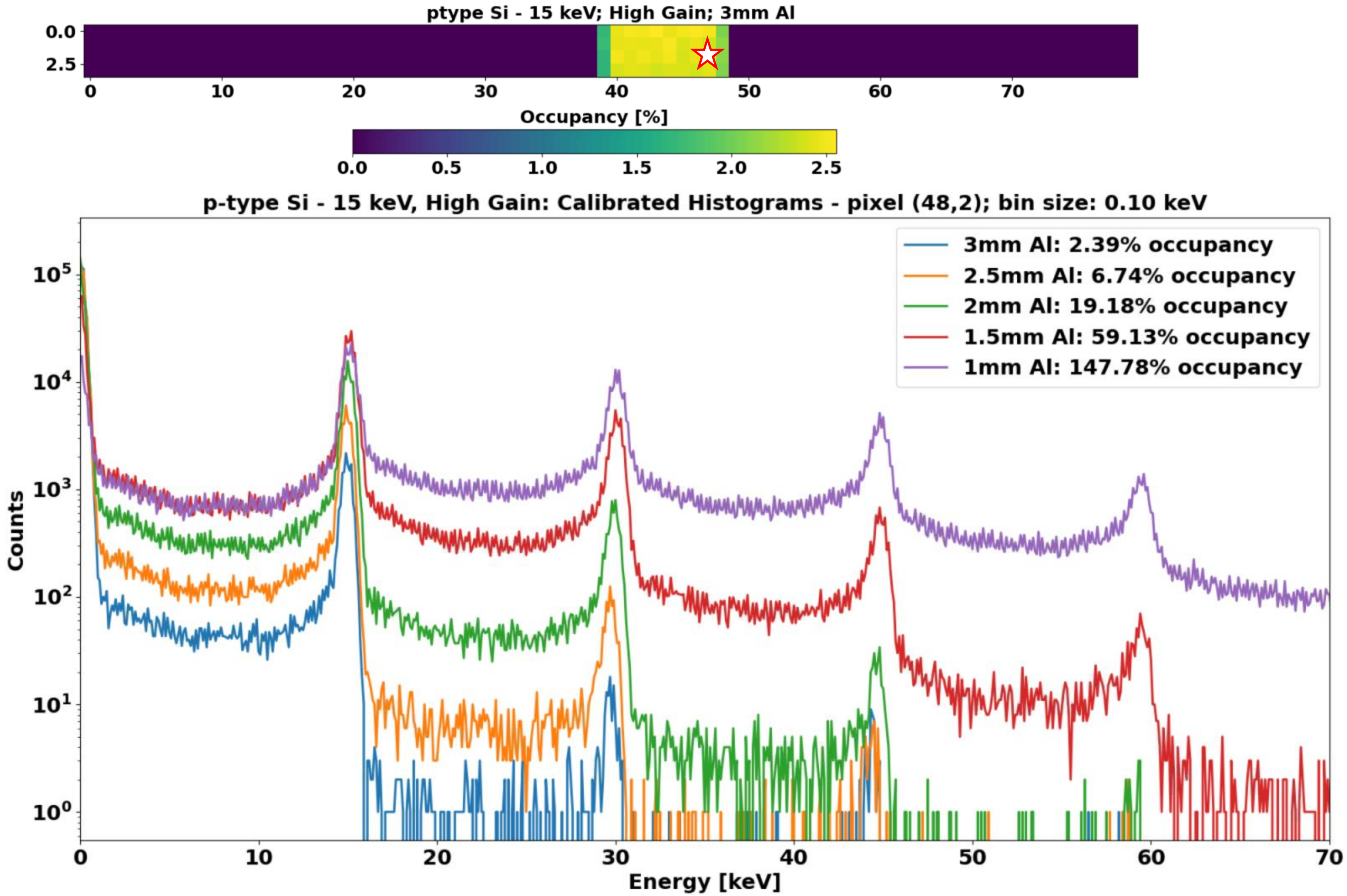
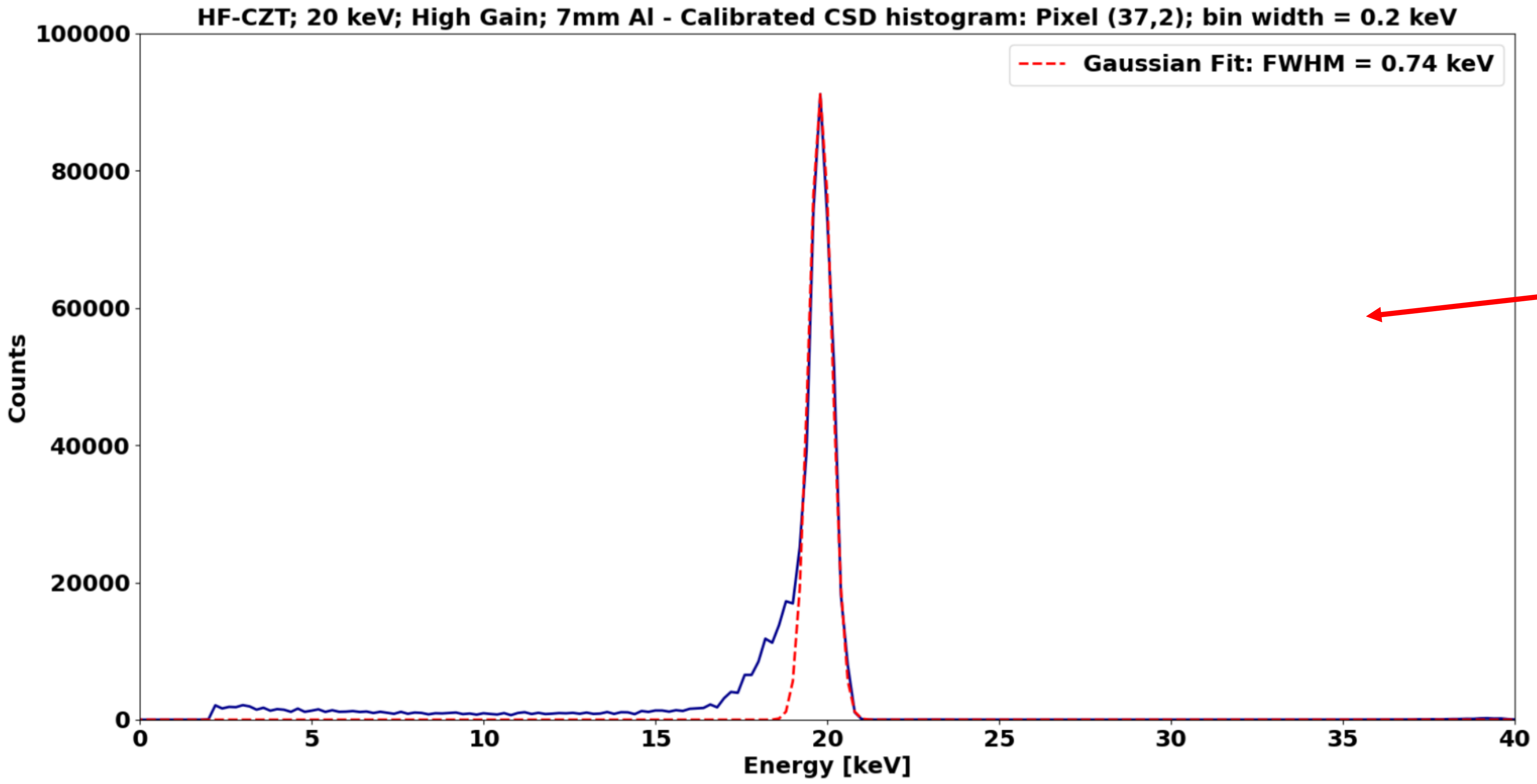
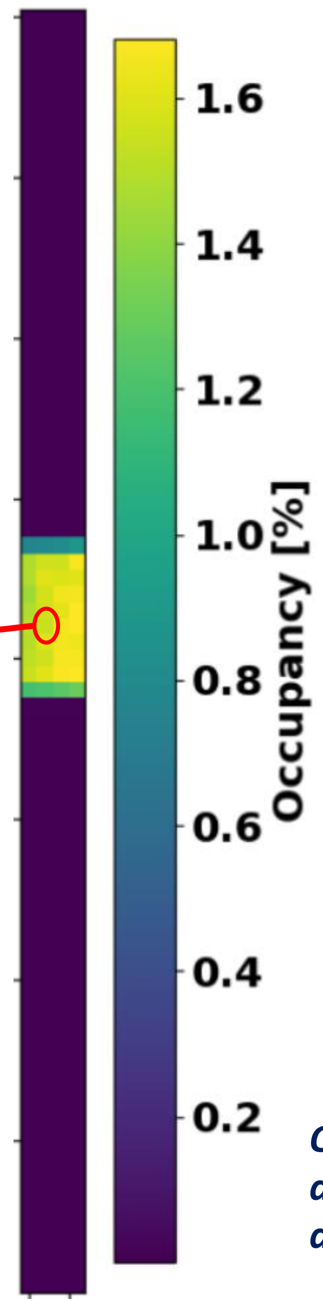


Calibrated histograms of pixel (48,2)

diamond – HF-CZT Characterisation

<u>HF-CZT; 20 keV; High Gain; 7 mm Al</u>





Occupancy across fast-data channel

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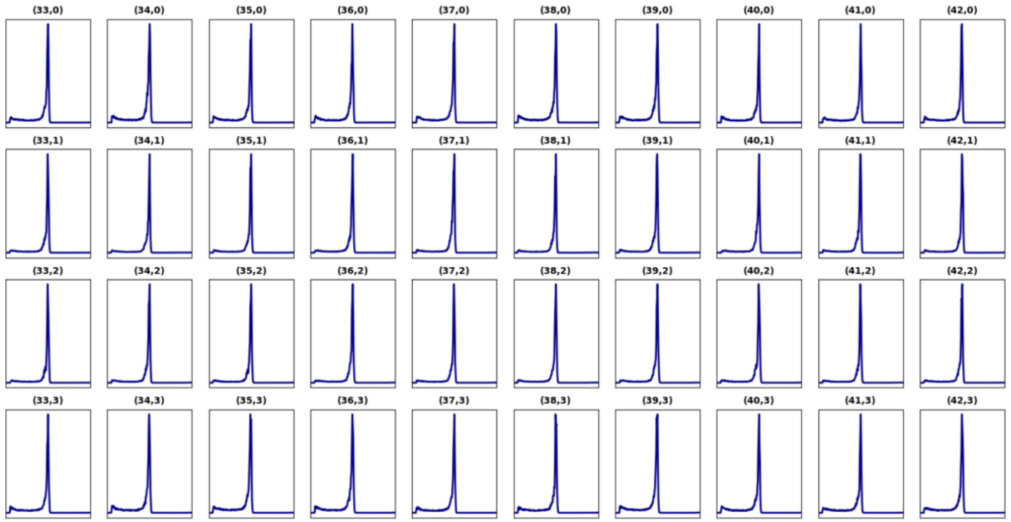
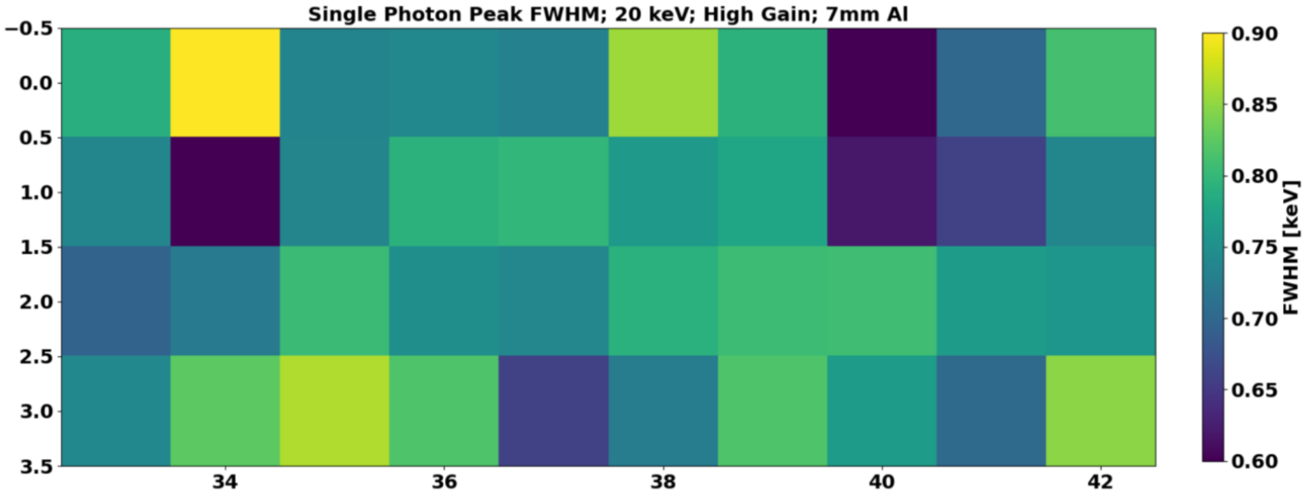
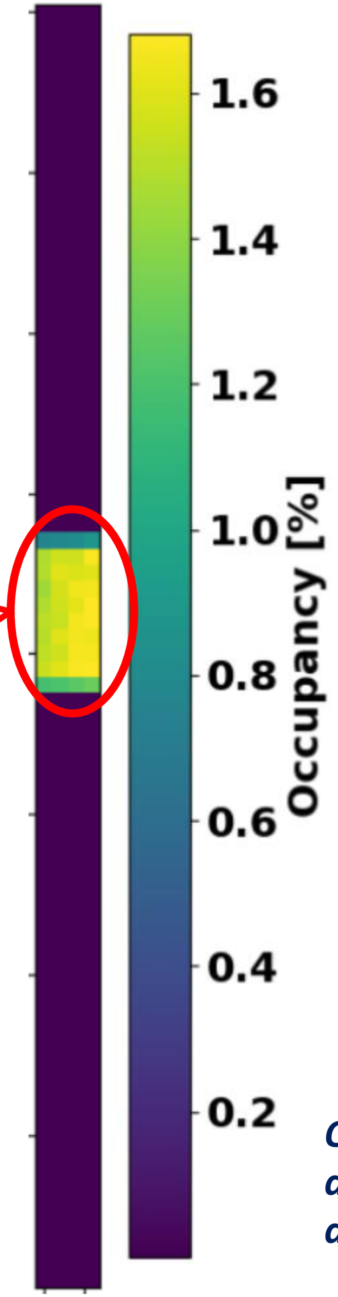


Calibrated CSD histograms in beam area



Single photon FWHM in beam area



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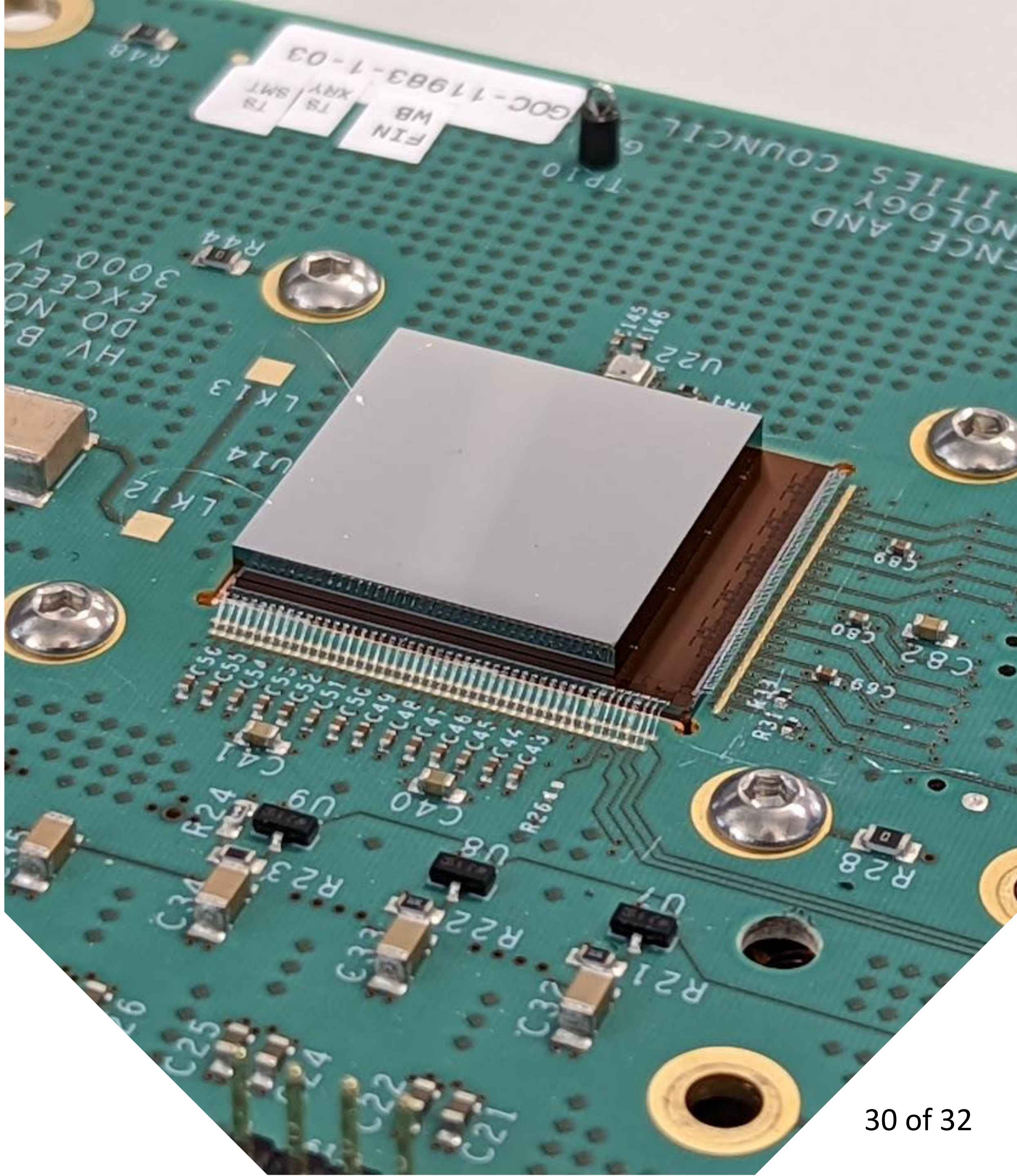


Next Steps

Achieving a 20-channel fast data output

- Reading out the full 80×80 array using the fast data

Further lab-based ASIC and sensor characterisation

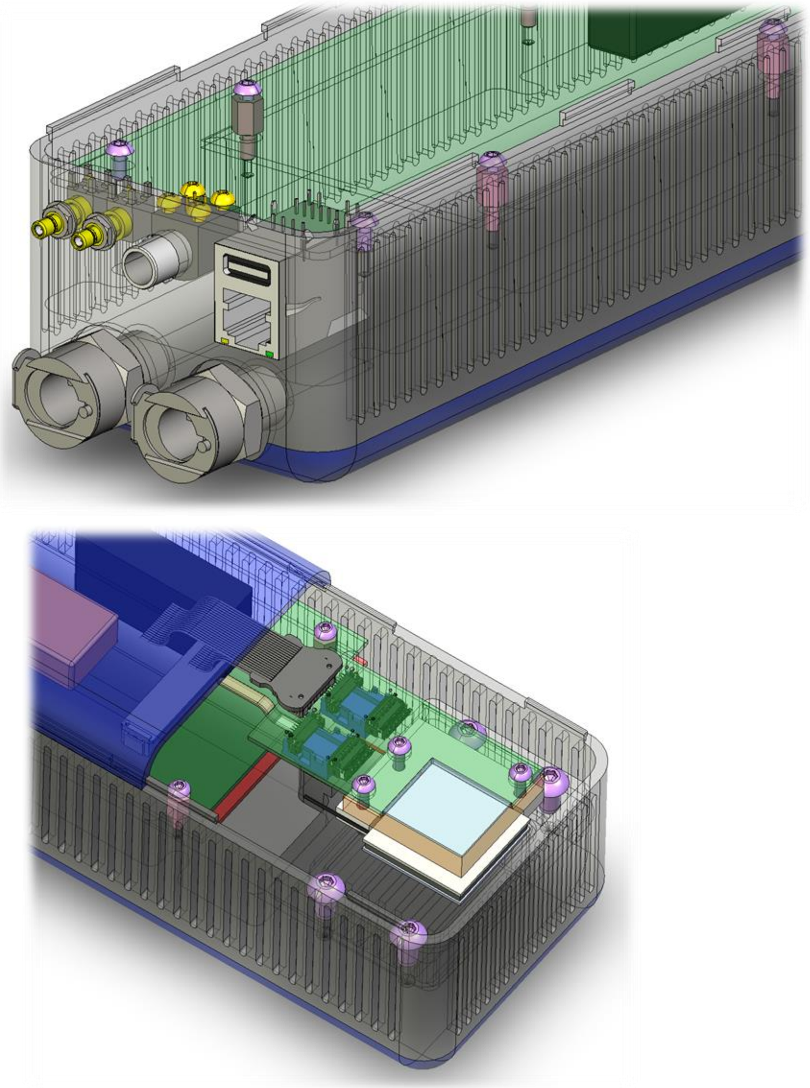
Implementation of in-FPGA histogramming

Delivery of HEXITEC$_{MHz}$ detector system

- Smaller, form factor production-grade system

Delivering Science

- 5D-CT for Materials Science – University of Manchester
- Mammography – Institute of Cancer Research, UK
- Security imaging – Nottingham-Trent University



Possible designs for HEXITEC$_{MHz}$ detector system

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Summary

- HEXITEC$_{MHz}$ is a fully-spectroscopic X-Ray detector capable of operating continuously at 1 MHz

Parameter	HEXITEC$_{MHz}$
Max Frame Rate (MHz)	1
Max Spectroscopic Flux (ph s^{-1} mm^{-2})	>10^6
Digitisation	On-chip
Detector Type	Integrating
Measured FWHM	0.50 keV @ 15 keV in p-type Si 0.74 keV @ 20 keV in HF-CZT

HEXITEC$_{MHz}$ testing in February 2022

- Testing underway to characterise the ASIC and optimise register settings

- The next year will include delivery of a full 80×80 pixel readout and a new smaller form-factor system

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If you have any further questions, please contact me at: ben.cline@stfc.ac.uk

Backup Slides

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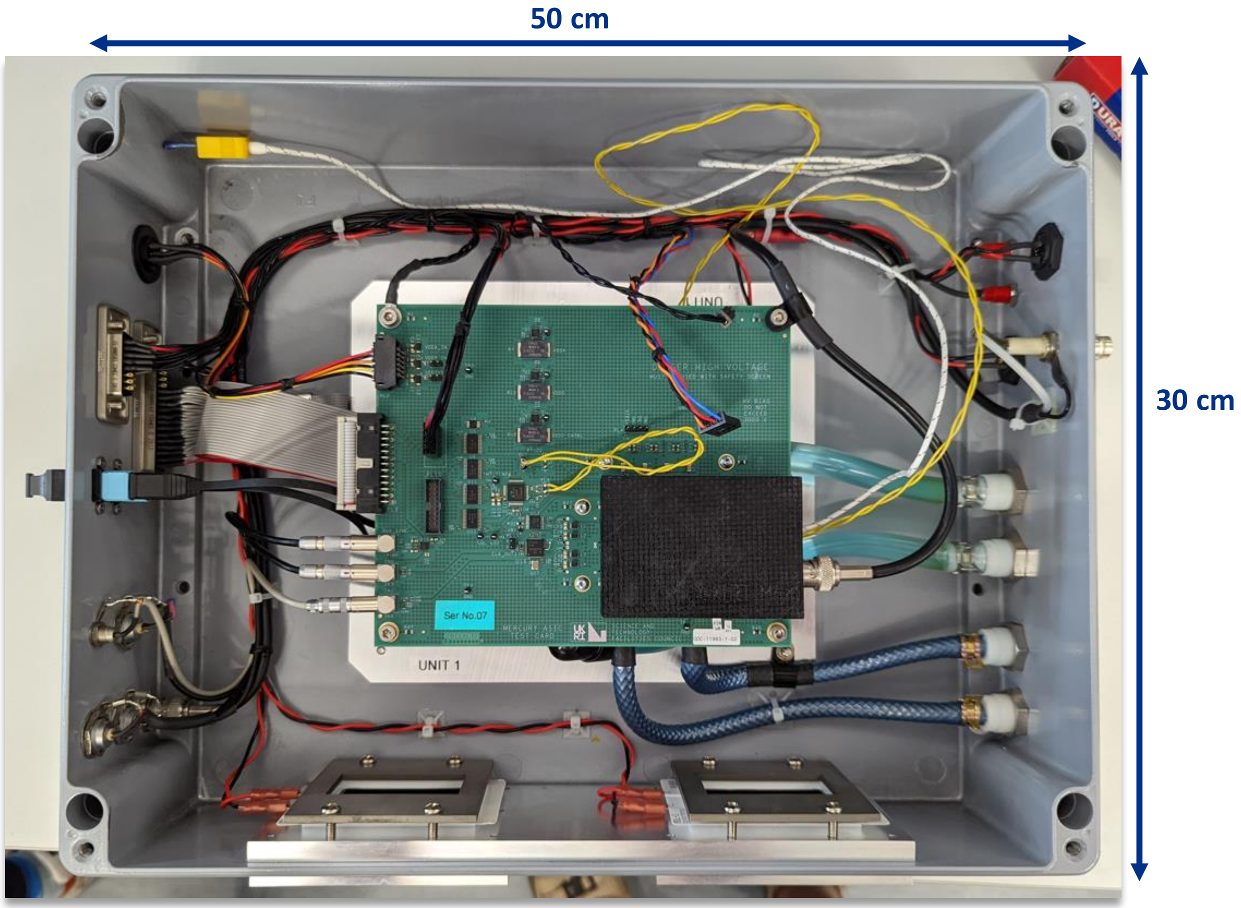
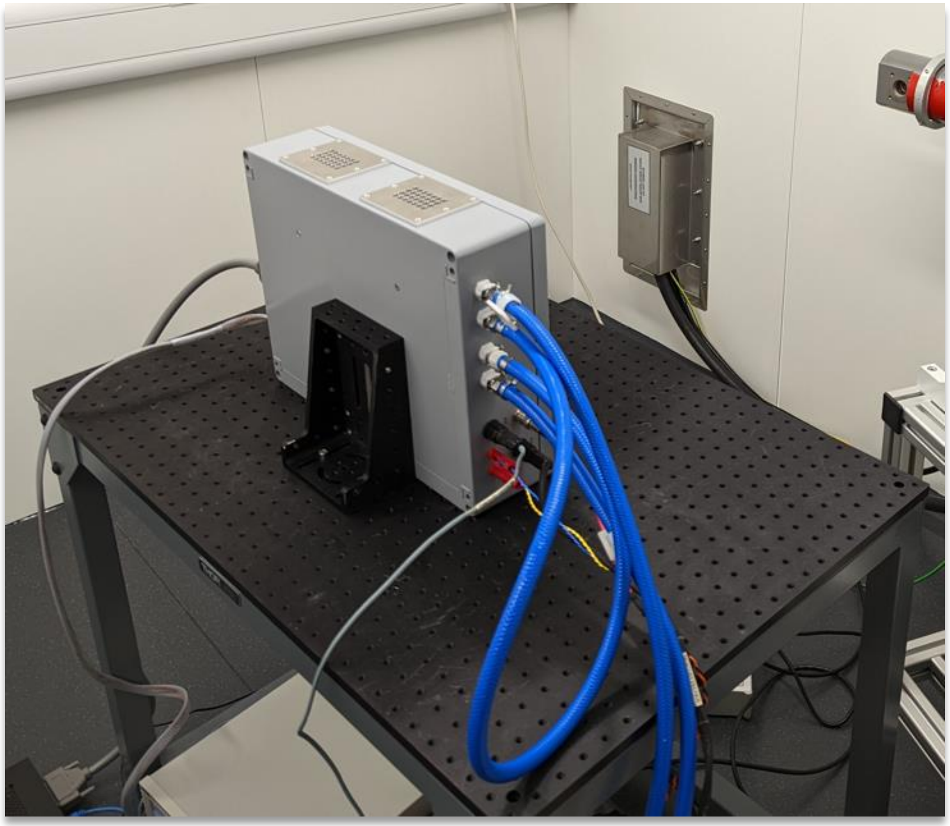
Testing – Test Setup



HEXITEC$_{MHz}$ test enclosure (interior)



HEXITEC$_{MHz}$ test enclosure (exterior)

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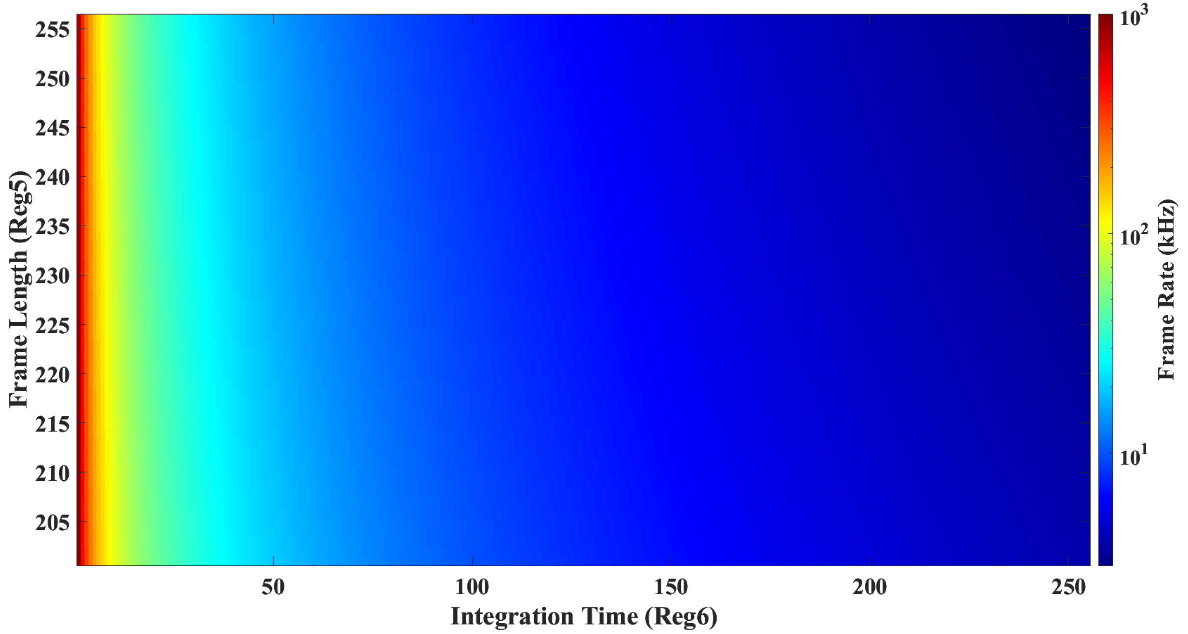
Available Frame Rates

- **Two chip registers can be altered**:
  - Frame Time: **200**→255 clocks frame^{-1}
  - Integration Length: **1** →255 frames

Default values



Available Frame Rates

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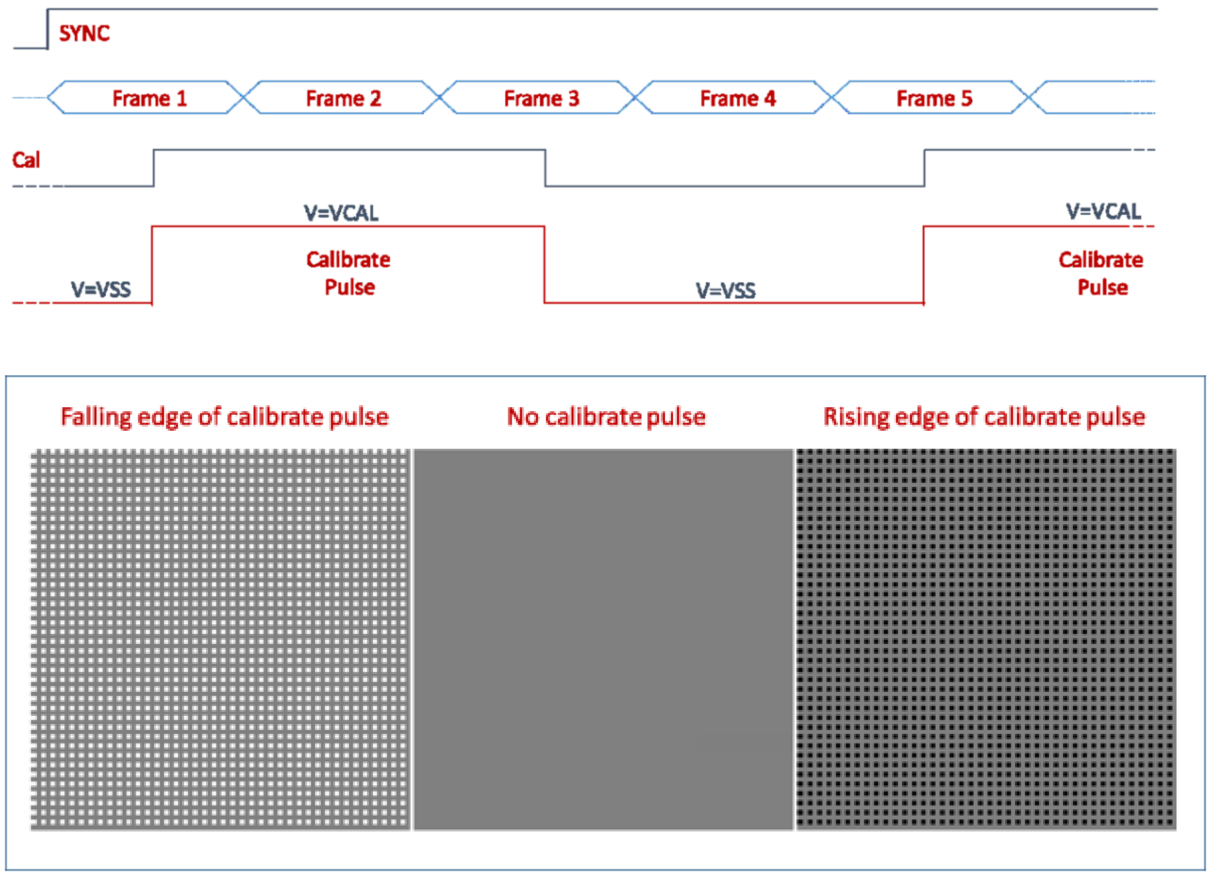
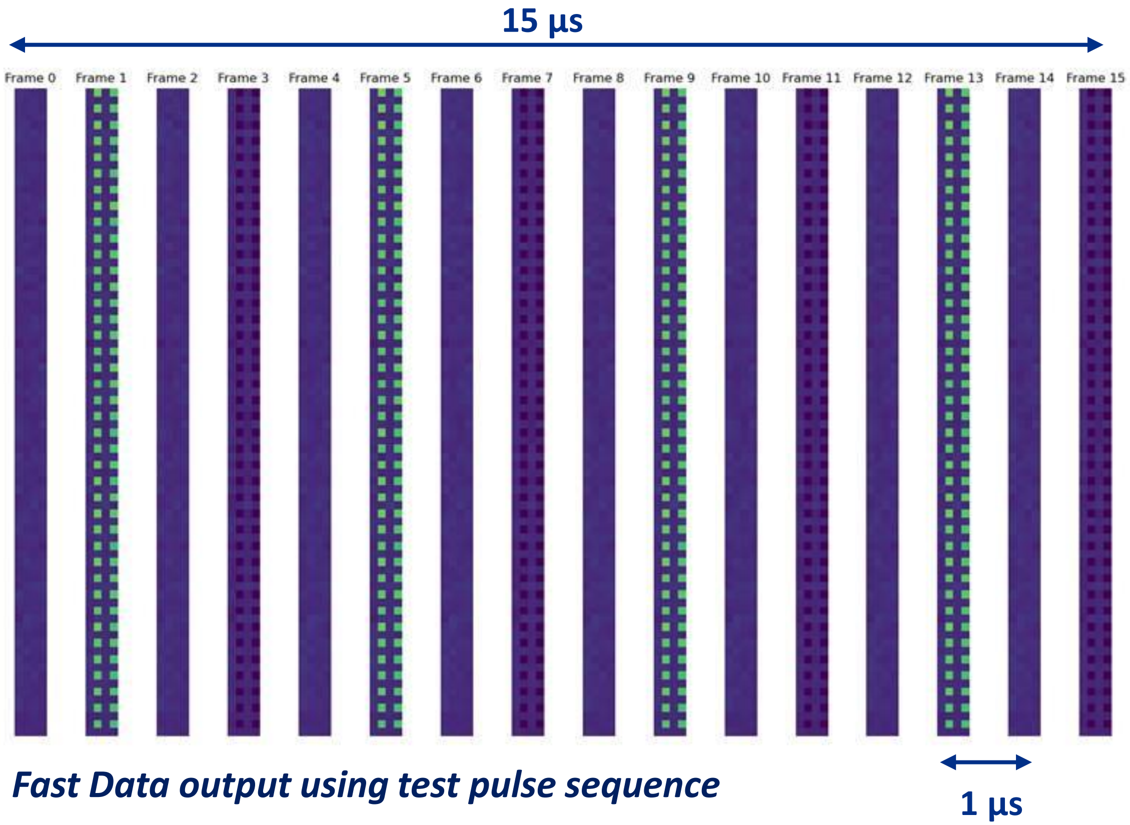
Test Pulse Sequence



Test pulse sequence



Fast Data output using test pulse sequence

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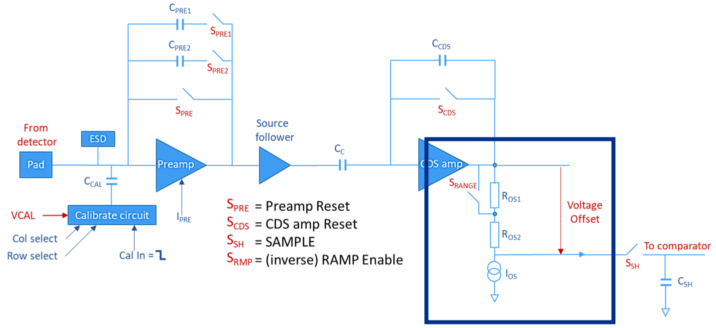
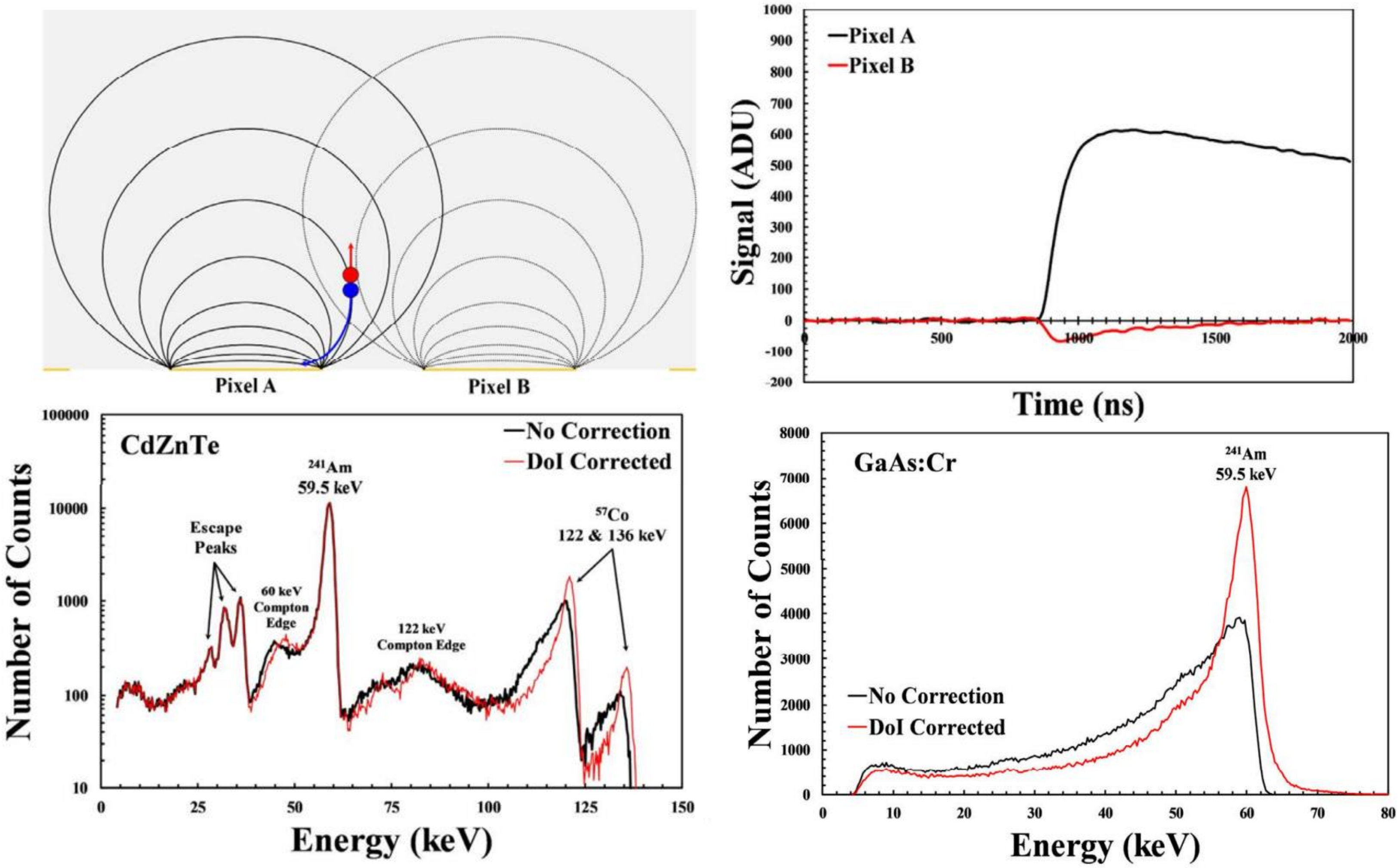
Front End – Negative Offset Circuit



Negative offset circuit

Potential application - Results from Veale et al., 2019;

- **Data collected with STFC's PIXIE ASIC** (DOI: 10.1016/j.nima.2019.01.045)



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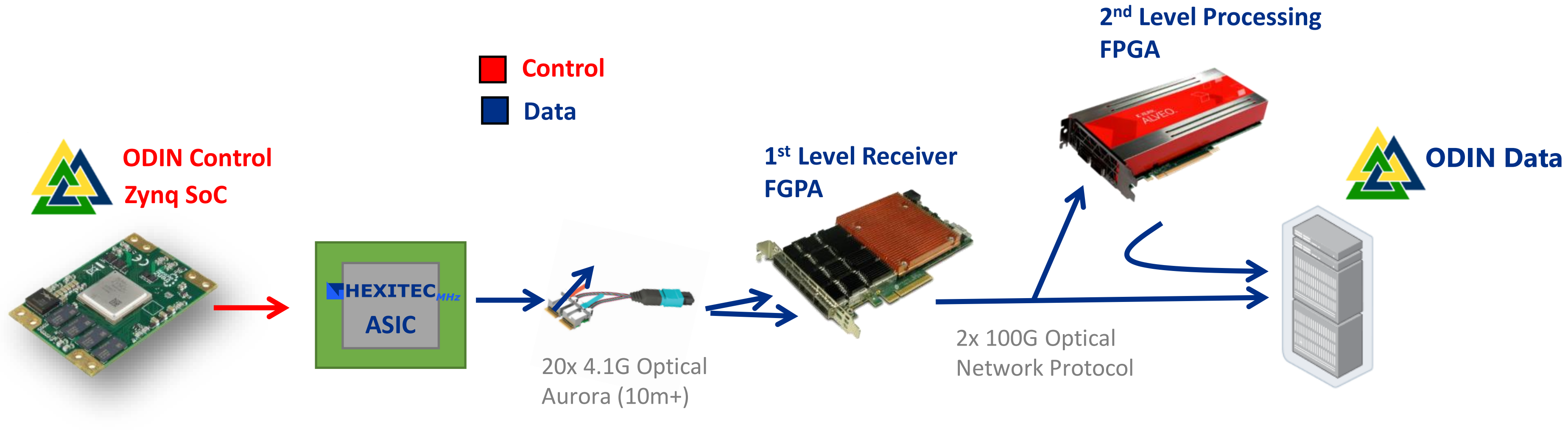
Data Output Plane



Data output path schematic

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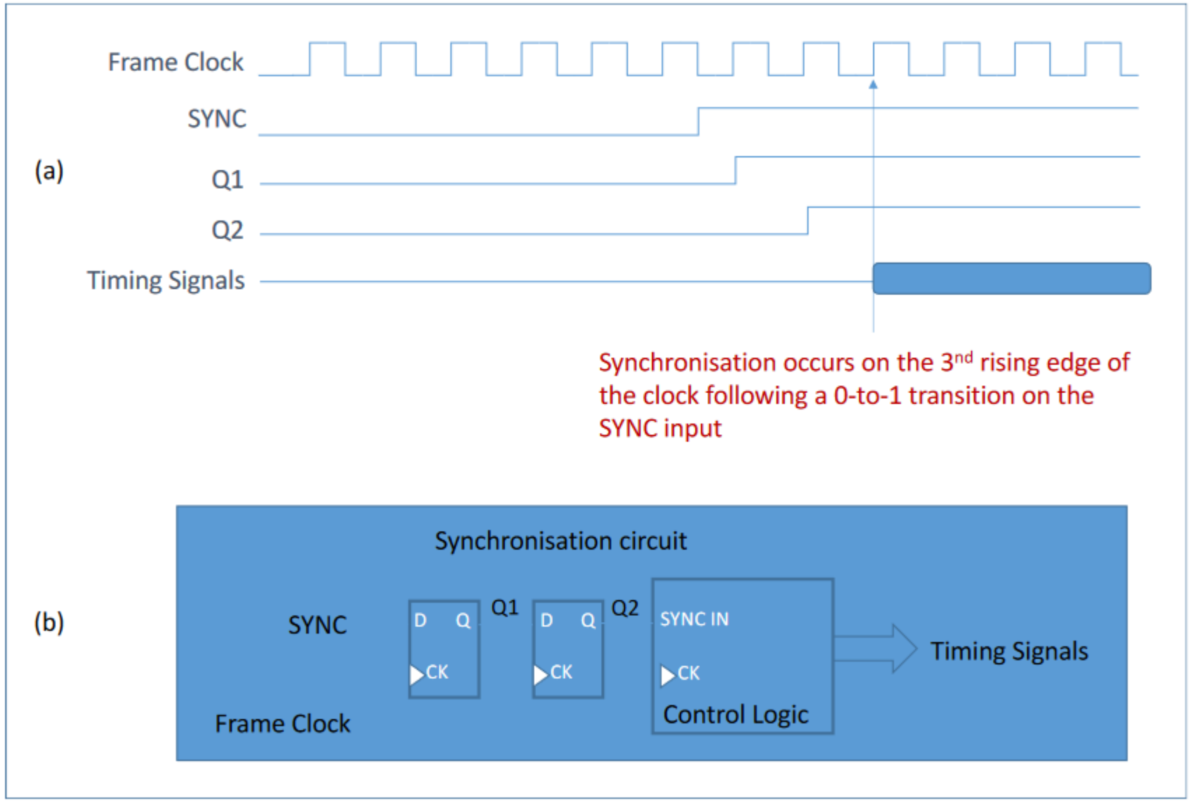
Synchronising the ASIC



Synchronisation circuit

- ASIC synchronised by **controlling transition of SYNC input**
  - Logic 0 → logic 1
  - Synchronisation occurs on 3rd subsequent rising clock edge
- Used for external synchronisation and multi-ASIC systems

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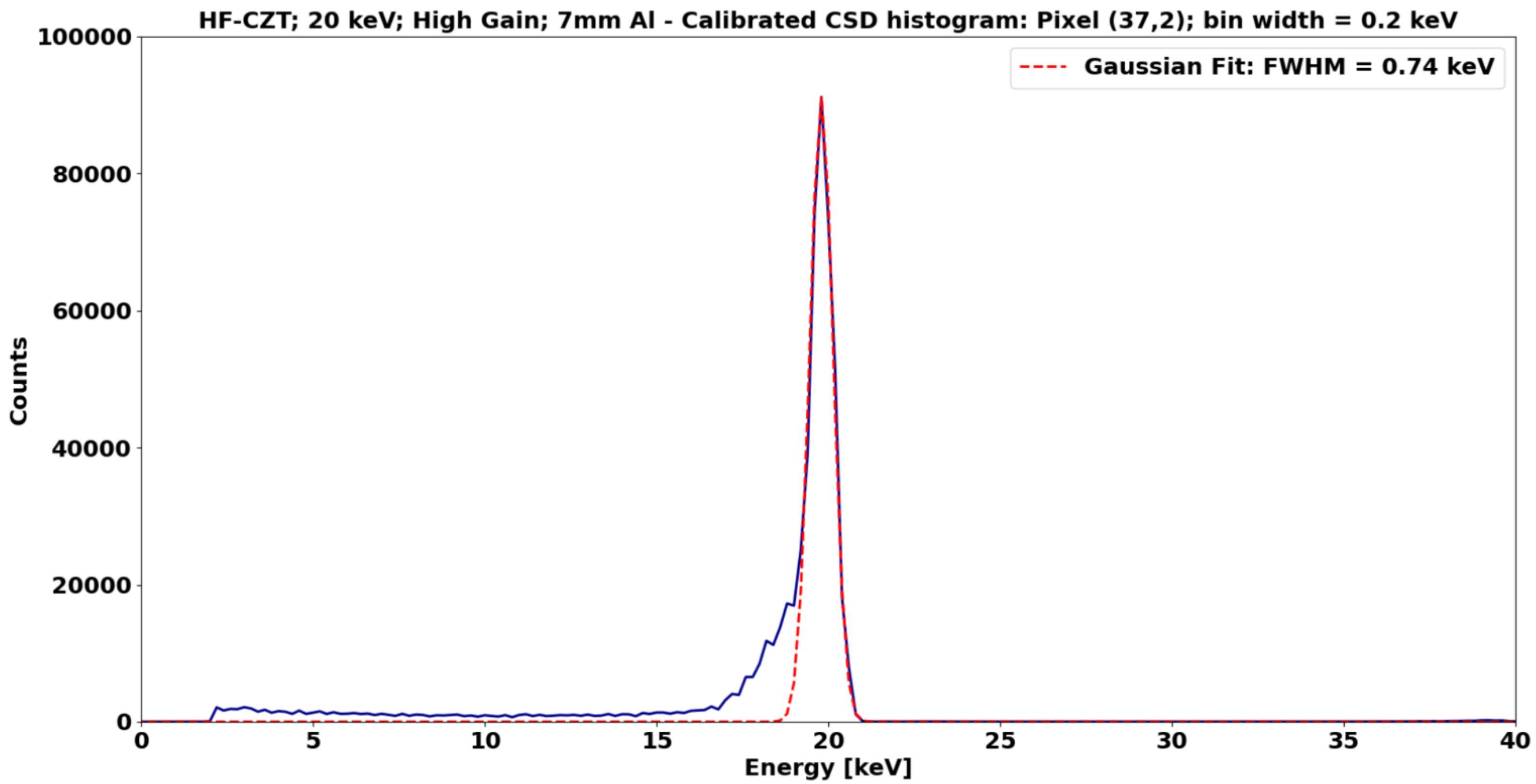
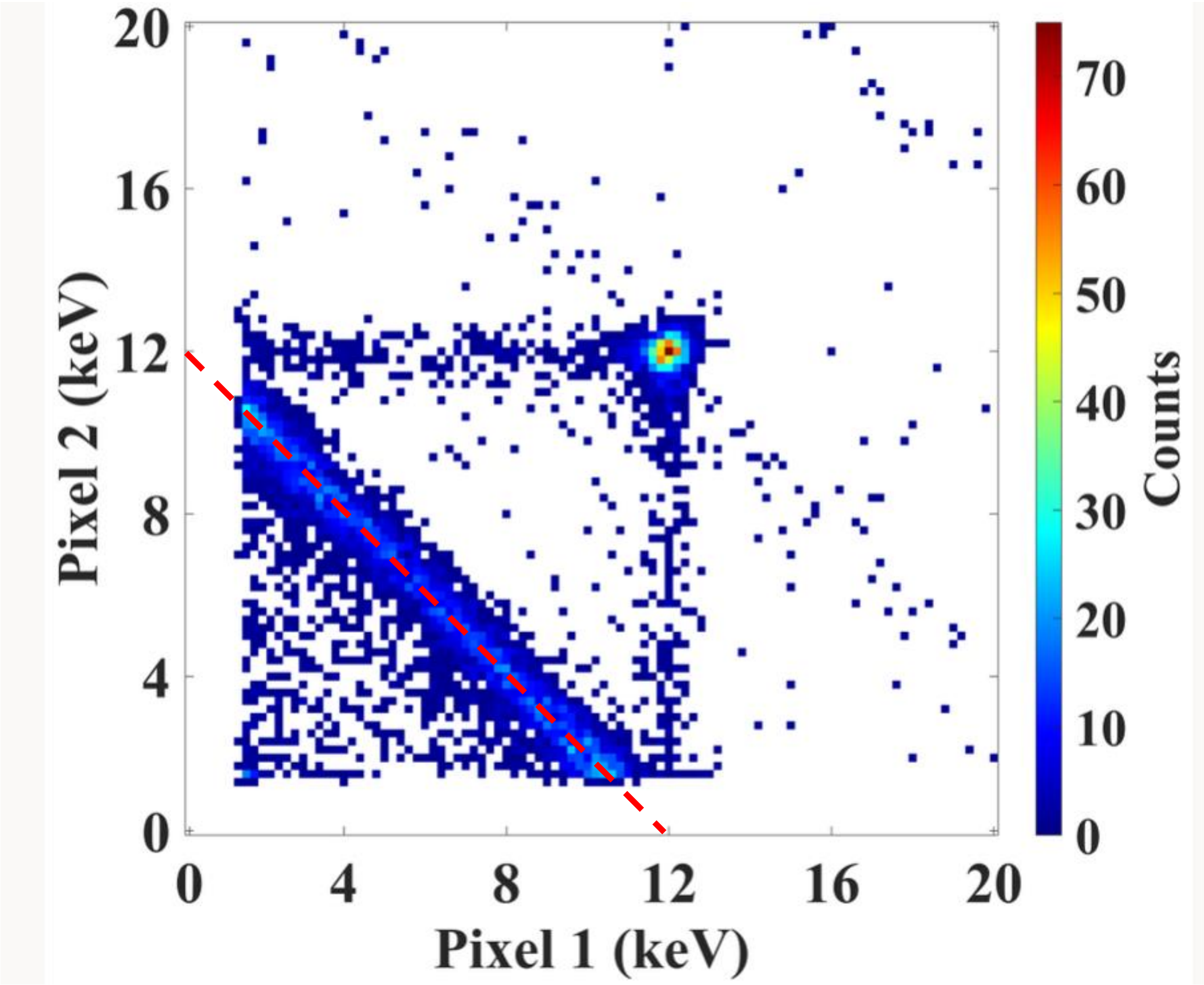
Electronic Noise Contribution



- **HF-CZT FWHM @ 20 keV ≈ 0.7 keV**
- **HF-CZT w factor = 4.67 eV**
- **→ ENC =** $\sqrt{700 \times 4.67} \approx 57\ e^{-}$

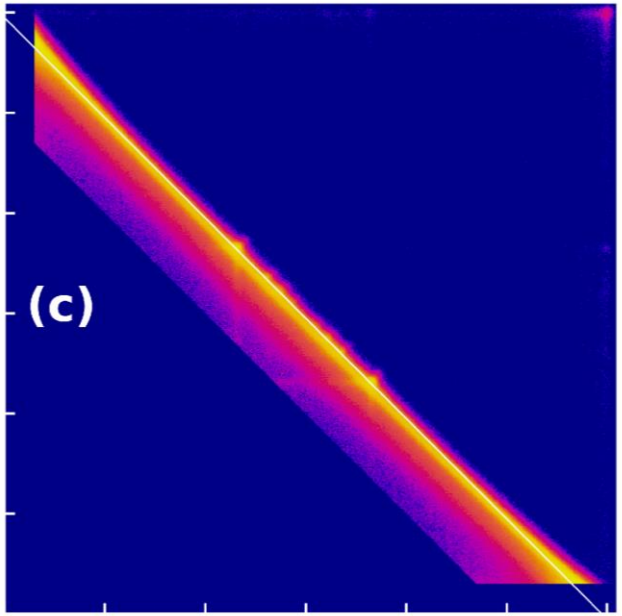
diamond – Charge Sharing

P-type Si; 12 keV; High Gain; 1.5mm Al



Energy-components of two-pixel charge-shared events at 12 keV

HF – CdZnTe
Frame occupancy : 0.4%



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Charge Sharing and Charge Loss in High-Flux Capable Pixelated CdZnTe Detectors

by Kjell A. L. Koch-Mehrin [1,*], Sarah L. Bugby [2], John E. Lees [1], Matthew C. Veale [3] and Matthew D. Wilson [3]

[1] Space Research Centre, Department of Physics & Astronomy, University of Leicester, Leicester LE1 7RH, UK
[2] Centre for Imaging Science, Department of Physics, Loughborough University, Loughborough LE11 3TU, UK
[3] STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, UK
[*] Author to whom correspondence should be addressed.

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TSVs on HEXITEC

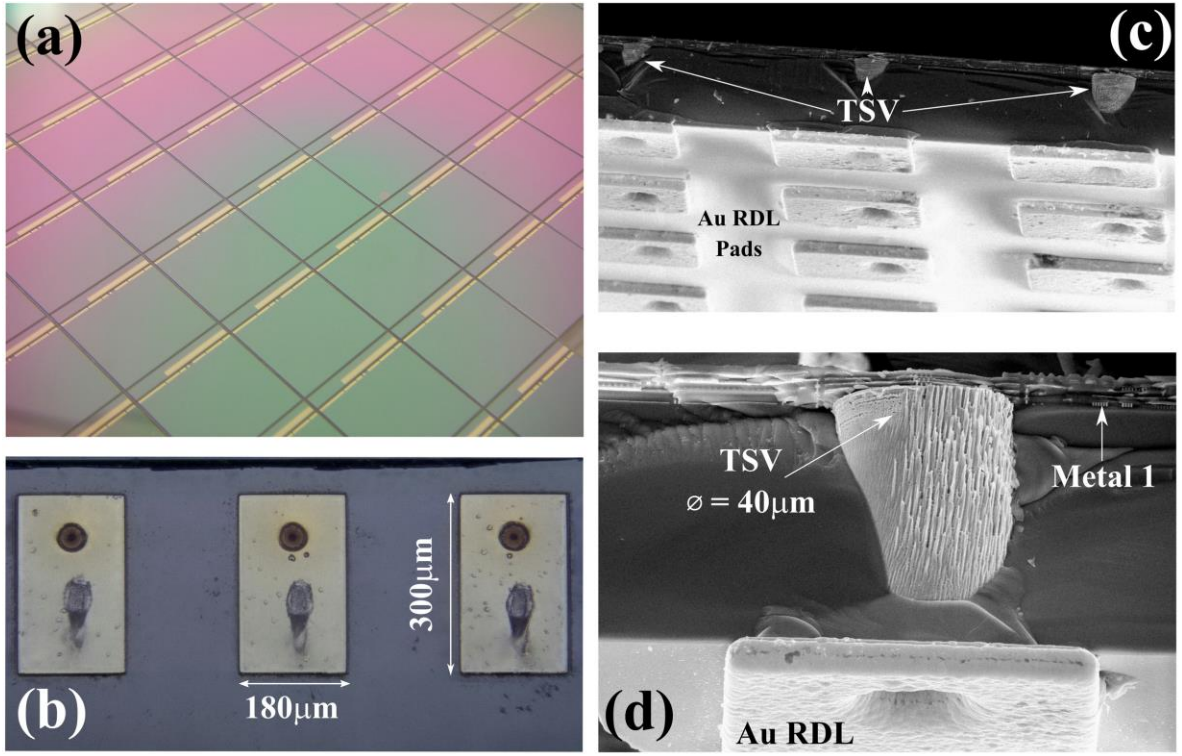

Fig. 2. (a) I/O pads on reverse of the 200 mm HEXITEC4S wafer post-TSV-last processing (b) RDL pads dimensions on ASIC's reverse. (c) SEM micrograph of exposed TSVs in cleaved test chip. (d) SEM micrograph showing contact between TSV and ASIC's bottom metal layer.

https://doi.org/10.1016/j.nima.2021.166083

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 1025, 11 February 2022, 166083

Characterisation of the $HEXITEC_{4S}$ X-ray spectroscopic imaging detector incorporating through-silicon via (TSV) technology

M.C. Veale [a], P. Booker [a], I. Church [a], L.L. Jones [a], J. Lipp [a], A. Schneider [a], P. Seller [a], M.D. Wilson [a], I. Chsherbakov [b], I. Kolesnikova [b], A. Lozinskaya [b], V. Novikov [b], O. Tolbanov [b], A. Tyazhev [b], A. Zarubin [b]

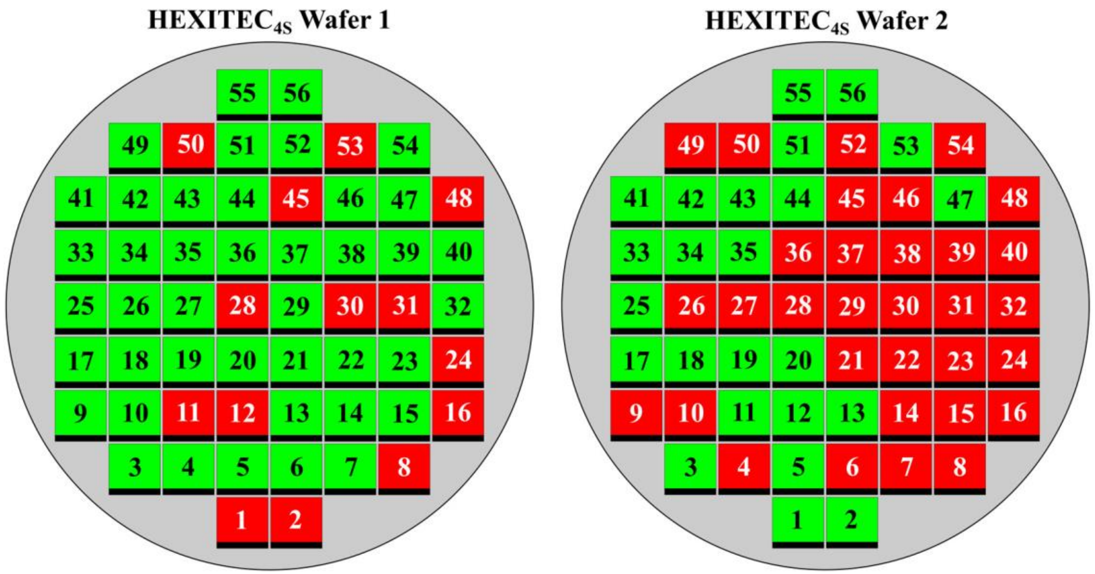

Fig. 4. Wafer maps showing results of probe testing. Green – functioning; Red – non functioning

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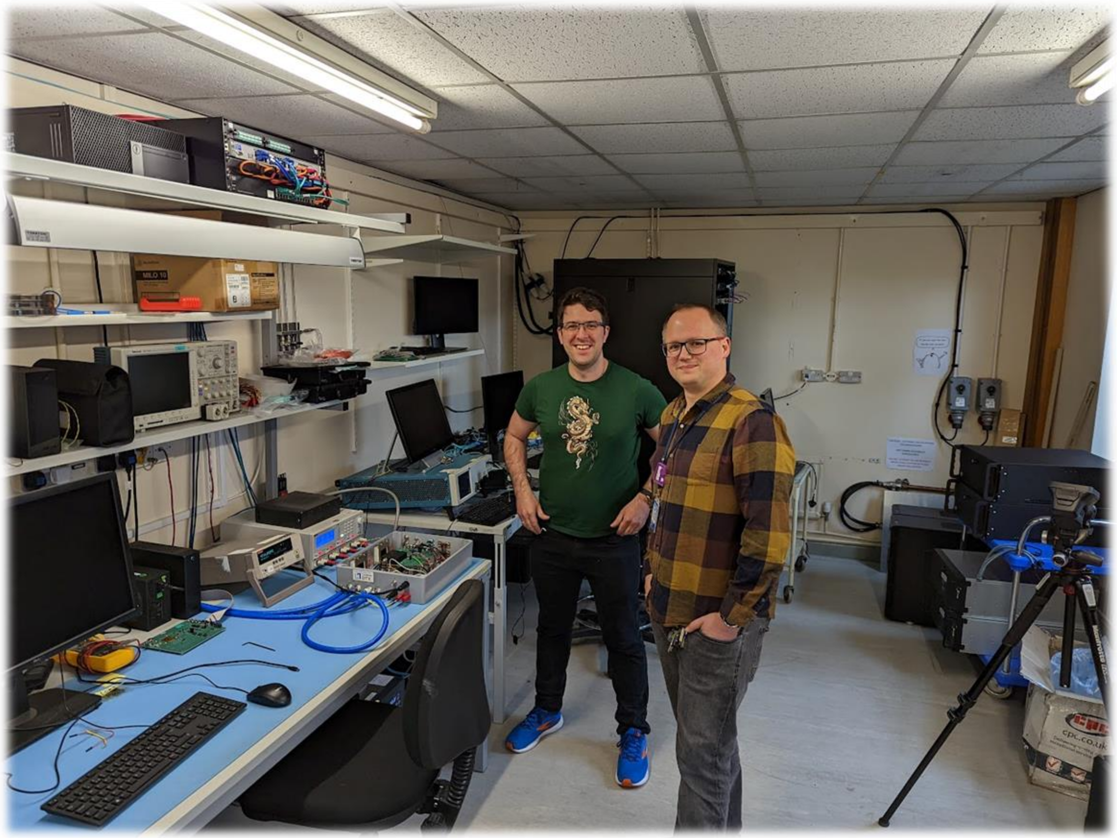
Next steps – Current Applications

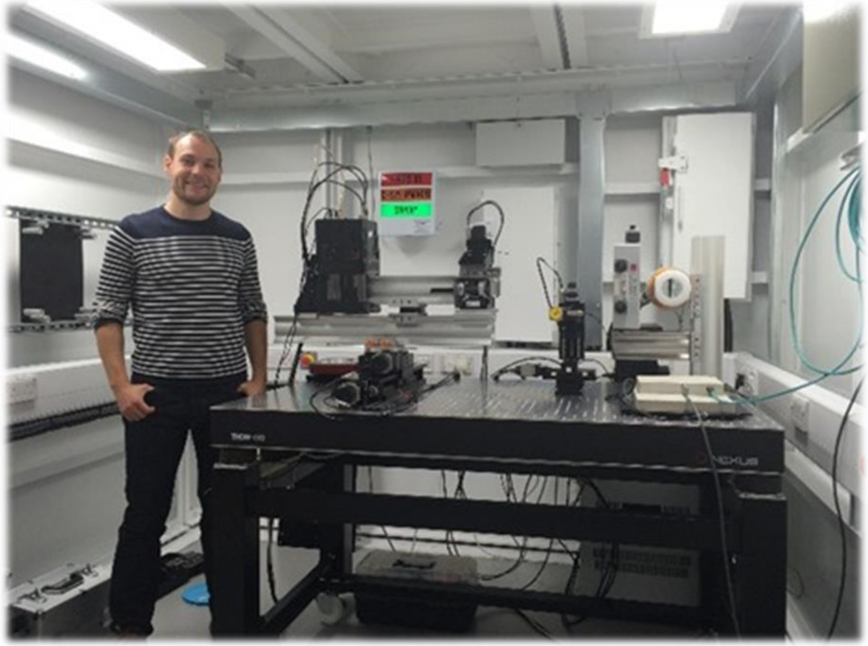
MIC-12-434: *On the feasibility of using HEXITEC$_{MHZ}$ and fully-spectral x-ray imaging to detect breast tumours: an in-silico study*



The ROYAL MARSDEN
NHS Foundation Trust

ICR The Institute of Cancer Research

New Project: 5DCT – *Dynamic Colour X-ray Computed Tomography*

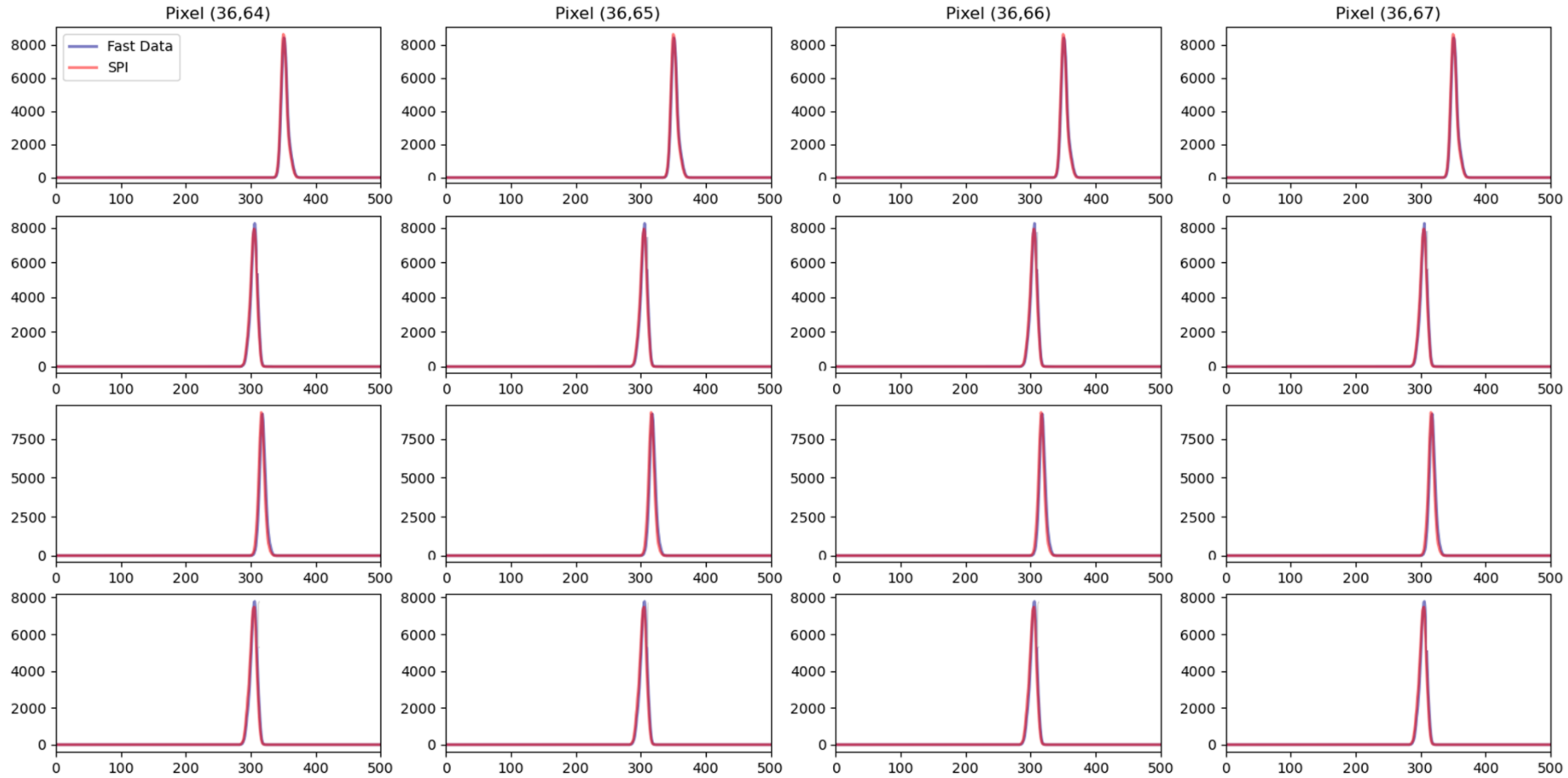


NXCT National X-Ray Computed Tomography

Department for Business, Energy & Industrial Strategy

UKRI Biotechnology and Biological Sciences Research Council

Testing – SPI vs Fast Data Comparison



Comparison of fast data and SPI measurements using test pulse

Fast data matches SPI output ☺

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