Science and Technology Facilities Council

Characterisation of Redlen High-Flux CdZnTe at >10^6 ph s^{-1} mm^{-2} using

HEXITEC$_{MHz}$

Ben Cline[a,1], D. Banks[a], S. Bell[a], I. Church[a], A. Davis[a], T. Gardiner[a], J. Harris[a], M. Hart[a], L. Jones[a], T. Nicholls[a], J. Nobes[a], S. Pradeep[a], M. Roberts[a], D. Sole[a], M.C. Veale[a], M.D. Wilson[a], V. Dhamgaye[b], O. Fox[b], K. Sawhney[b].

[a]UKRI STFC Rutherford Appleton Laboratory
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02/07/2024

Agenda

1 HEXITEC$_{MHz}$ Overview

The next generation of HEXITEC systems

2 Redlen HF-CZT Overview

CdZnTe for use at high X-ray fluxes (<10^9 ph s^{-1} mm^{-2})

3 Initial HF-CZT Test Results

Results from HF-CZT characterisation carried out at the DLS B16 Test Beamline in December 2022

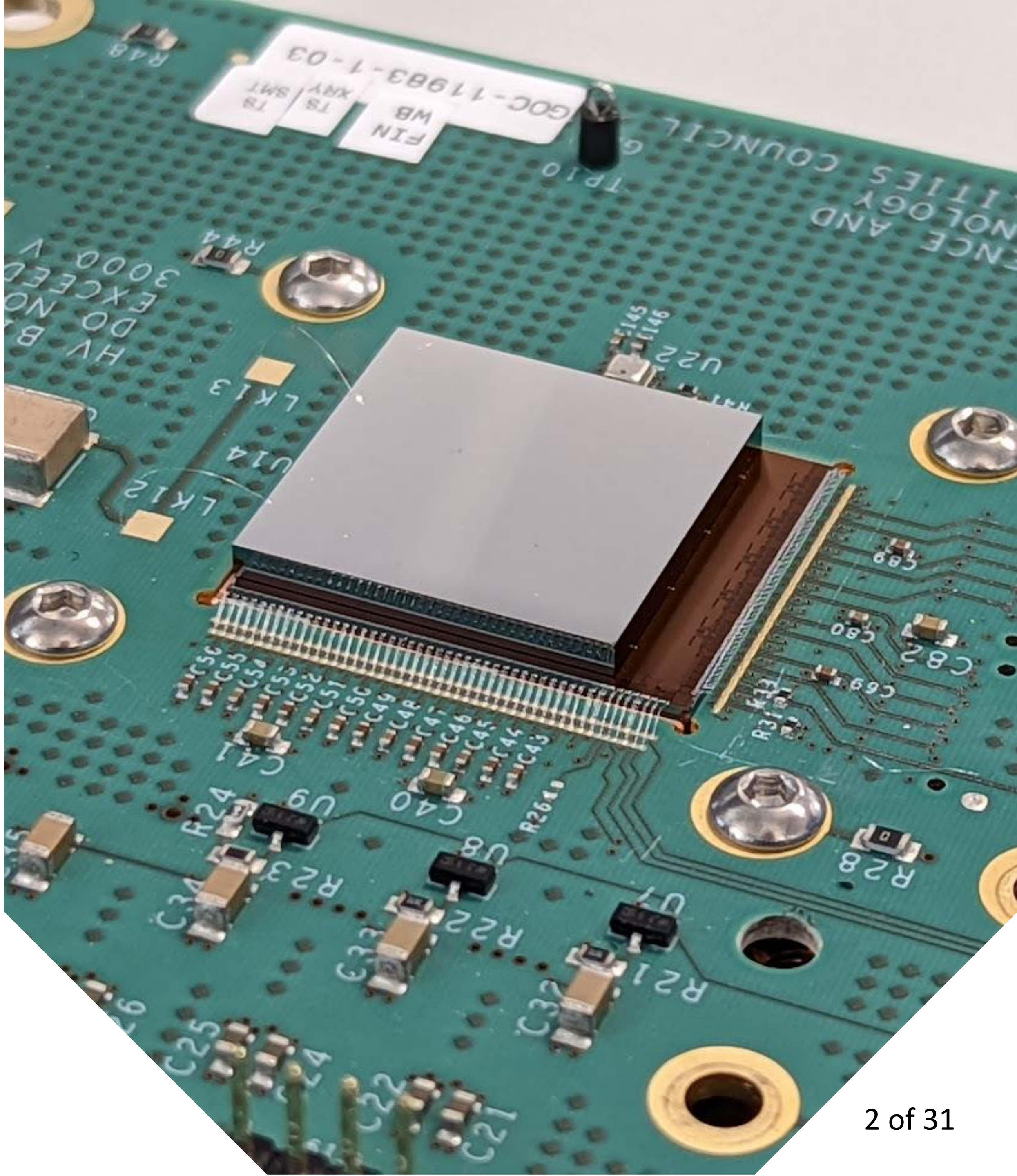
4 Recent HF-CZT Test Results

Results from HF-CZT characterisation carried out at the DLS B16 Test Beamline in December 2023

5 Next Steps

Future Work planned

Science and Technology Facilities Council



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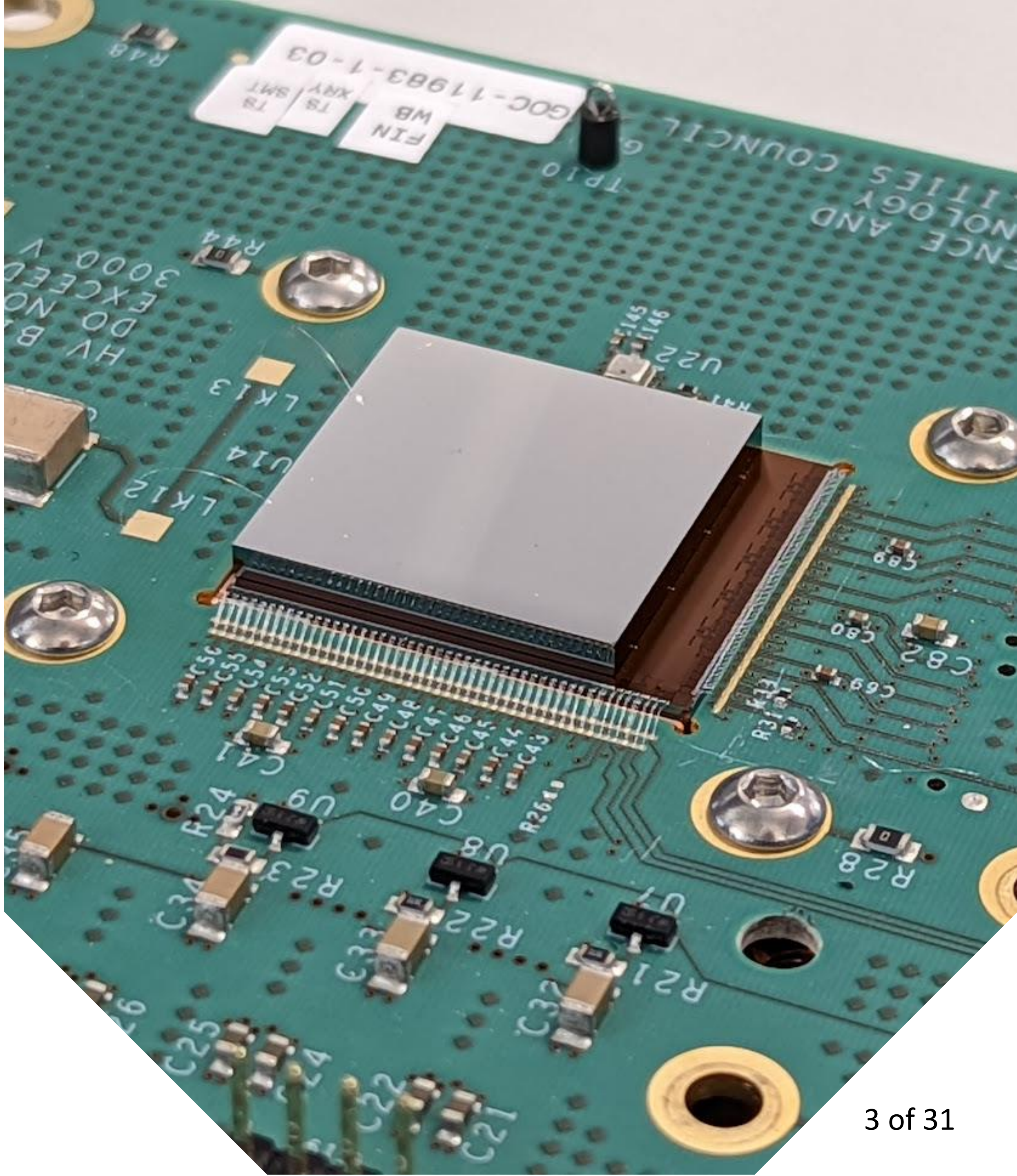
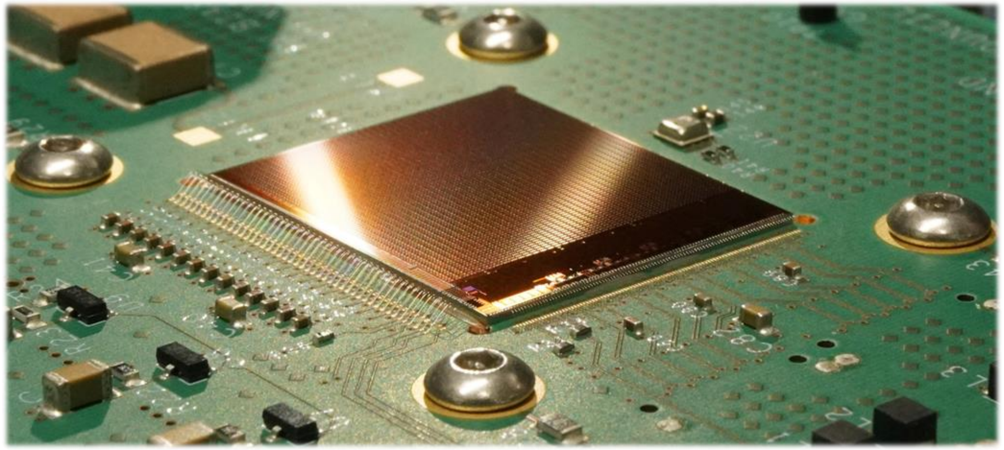


HEXITEC$_{MHz}$

New fully spectroscopic X-ray imaging detector:

- **1 MHz continuous frame rate**
  - Spectroscopic X-ray fluxes of **>10^6 ph s^{-1} mm^{-2}**
  - Facilitated by:
    - **Integrating Front End** with <70 e^- ENC
    - **12-bit on-chip digitisation** in TDCs
    - **20 × 4.1 Gbps serialisers** for data output
- 80 × 80 pixels on a 250 μm pitch



HEXITEC$_{MHz}$ ASIC

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)	9.81	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

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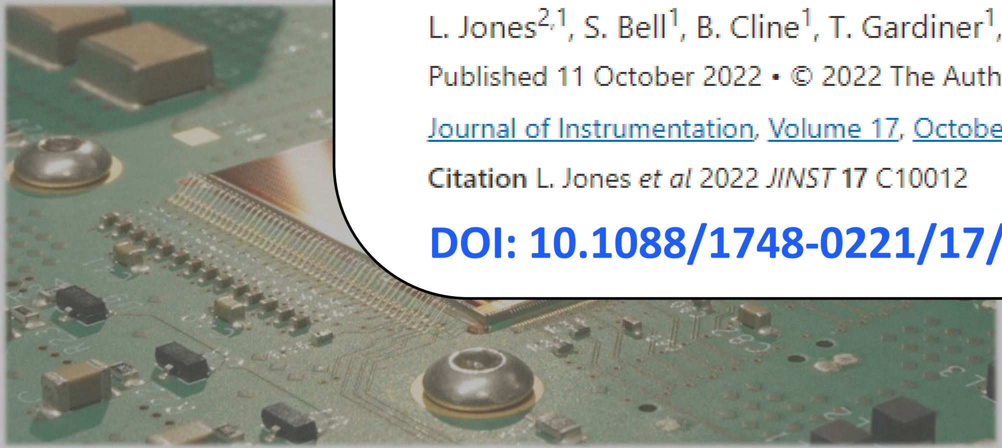
HEXITEC$_{MHz}$

New fully spectrosco…

- **1 MHz continuo…**
  - Spectrosco…
  - Facilitated …
    - **Integr…**
    - **12-bit…**
    - **20 × 4…**
- 80 × 80 pixels o…



HEXITEC$_{MHz}$ ASIC

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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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Journal of Instrumentation, Volume 17, October 2022

Citation L. Jones *et al* 2022 *JINST* **17** C10012

DOI: 10.1088/1748-0221/17/10/C10012

…ecifications

	…C	HEXITEC$_{MHz}$
		250
		80 × 80
		1000
		>10^6
	…o	**On-chip**
	Hold	**Integrating**
		100
		200
		300
FWHM@100keV (keV in CZT)	<1	<1
Power Consumption (W)	1.5	15

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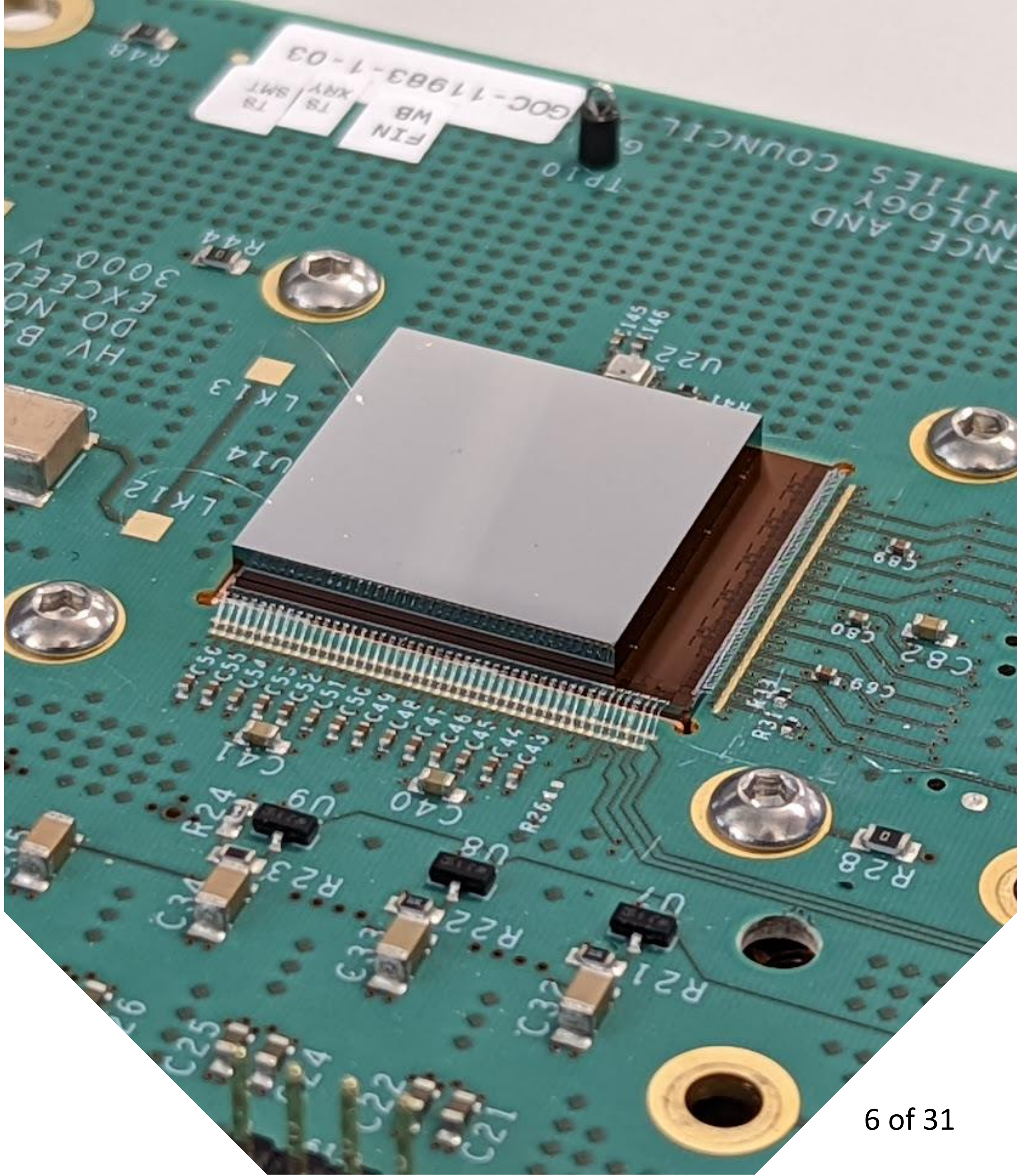

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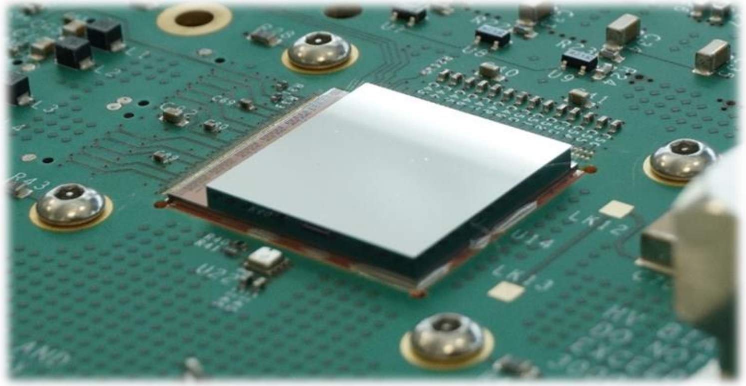
Redlen High-Flux Capable CdZnTe

- **Spectroscopic-grade CdZnTe**.
  - Optimised e^- transport properties and spectral resolution
  - **Poor h^+ lifetime and mobility ($\tau_h \approx 0.2$ µs, $\mu_h \approx 0.1\mu_e$)**
    - **h^+ trapping and polarization >10^6 ph^{-1} s^{-1} mm^{-2}**

- **Medical** and **Security CT applications** require:
  - >10^6 ph s^{-1} mm^{-2} X-ray fluxes

- **High-Flux Capable CdZnTe (HF-CZT)**
  - Introduced in 2017 by Redlen
  - ~10× increase in τ_h – allows operation <10^9 ph s^{-1} mm^{-2}

HEXITEC$_{MHz}$ HF-CZT detectors
- **2 mm thick sensors - two Pt electrodes, 25 µm inter-pixel gap**
- **ASIC hybridisation by UKRI STFC Interconnect - cured at 150°C**



HF-CZT sensor hybridised to HEXITEC$_{MHz}$ ASIC

Results from Thomas et al., 2017 [1]

Table 1. A summary of the measured charge transport properties of three "high-flux" Redlen CdZnTe detectors [14, 16].

	$\mu_e\tau_e$ ($\times10^{-4}$ cm^{2}V^{-1})	μ_e (cm^{2}V^{-1}s^{-1})	τ_e ($\times10^{-6}$ s)	$\mu_h\tau_h$ ($\times10^{-4}$ cm^{2}V^{-1})	μ_h (cm^{2}V^{-1}s^{-1})	τ_h ($\times10^{-6}$ s)
High Flux CdZnTe	11 ± 6	940 ± 190	1.2 ± 0.8	2.9 ± 1.4	114 ± 22	2.5 ± 1.4
Standard CdZnTe	100	1100	11	0.2	88	0.2

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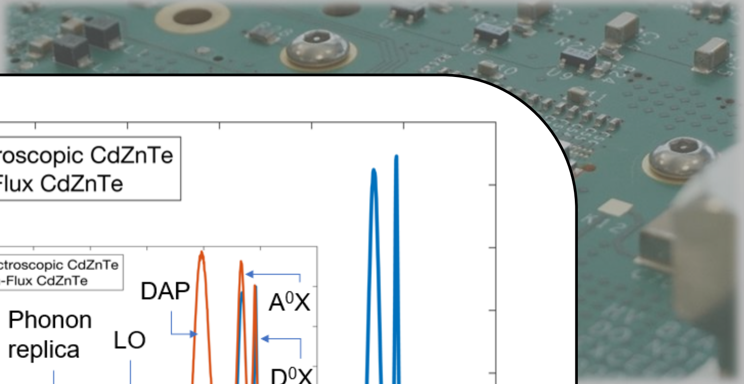
[1] DOI: 10.1088/1748-0221/12/12/C12045

Redlen High-Flux Capable CdZnTe

- **Spectroscopic-grad**
  - Optimised e
  - Poor h^+ life
    - h^+ trap
- **Medical** and **Sec**
  - $>10^6$ ph s^{-1}
- **High-Flux Capab**
  - Introduced
  - ~10× increa



EC$_{MHz}$ ASIC

1]

perties of three "high-flux" Redlen CdZnTe

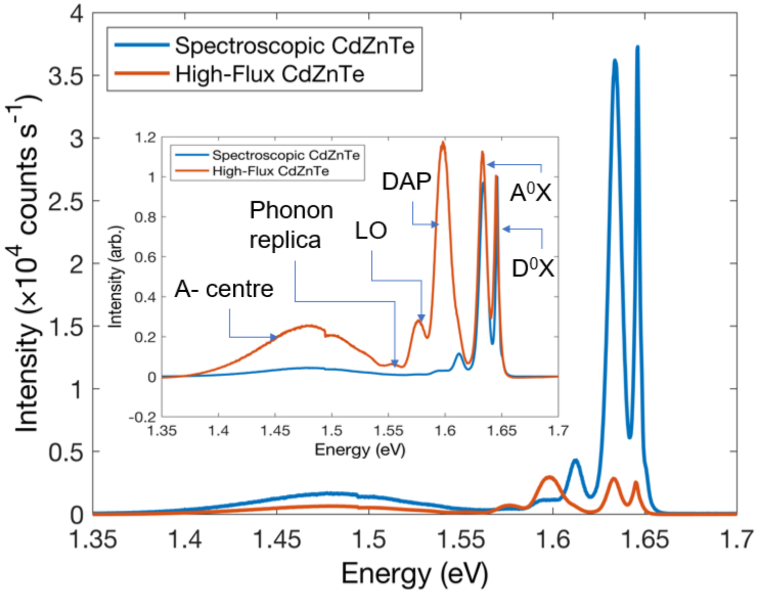
$\mu_h \tau_h$ ($\times 10^{-4}$ cm^2V^{-1})	μ_h ($cm^2V^{-1}s^{-1}$)	τ_h ($\times 10^{-6}$ s)
2.9 ± 1.4	114 ± 22	2.5 ± 1.4
0.2	88	0.2

HEXITEC$_{MHz}$ HF-C
- **2 mm thick sens**
- **ASIC hybridisation by UKRI STFC Interconnect - cured at 150°C**

Charge Transport Properties and Linearity of HF-CdZnTe Material

M. Bishop[1,2]*, B. D. Cline[1], E. Gimenez[3], F. K. Dejene[2], I. Braddock[1], J. Matheson[3], M. Larkin[1], M. Wilson[1], M. Veale[1], O. Fox[3], S. Bugby[2], S. Scully[3], S. Knowles[1], S. Zanettini[4], V. Dhamgaye[3]

POSTER ON DISPLAY THIS WEEK - SEE MAX BISHOP



4 K low temperature photoluminescence spectrum of HF-CdZnTe and spectroscopic CdZnTe. Taken with 400mA excitation led intensity, integration time has been converted into counts per second. (Insert) Spectrum normalised to D^0X peak. Notch at 1.48 eV is due to image stitching error.

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[1] DOI: 10.1088/1748-0221/12/12/C12045

Agenda

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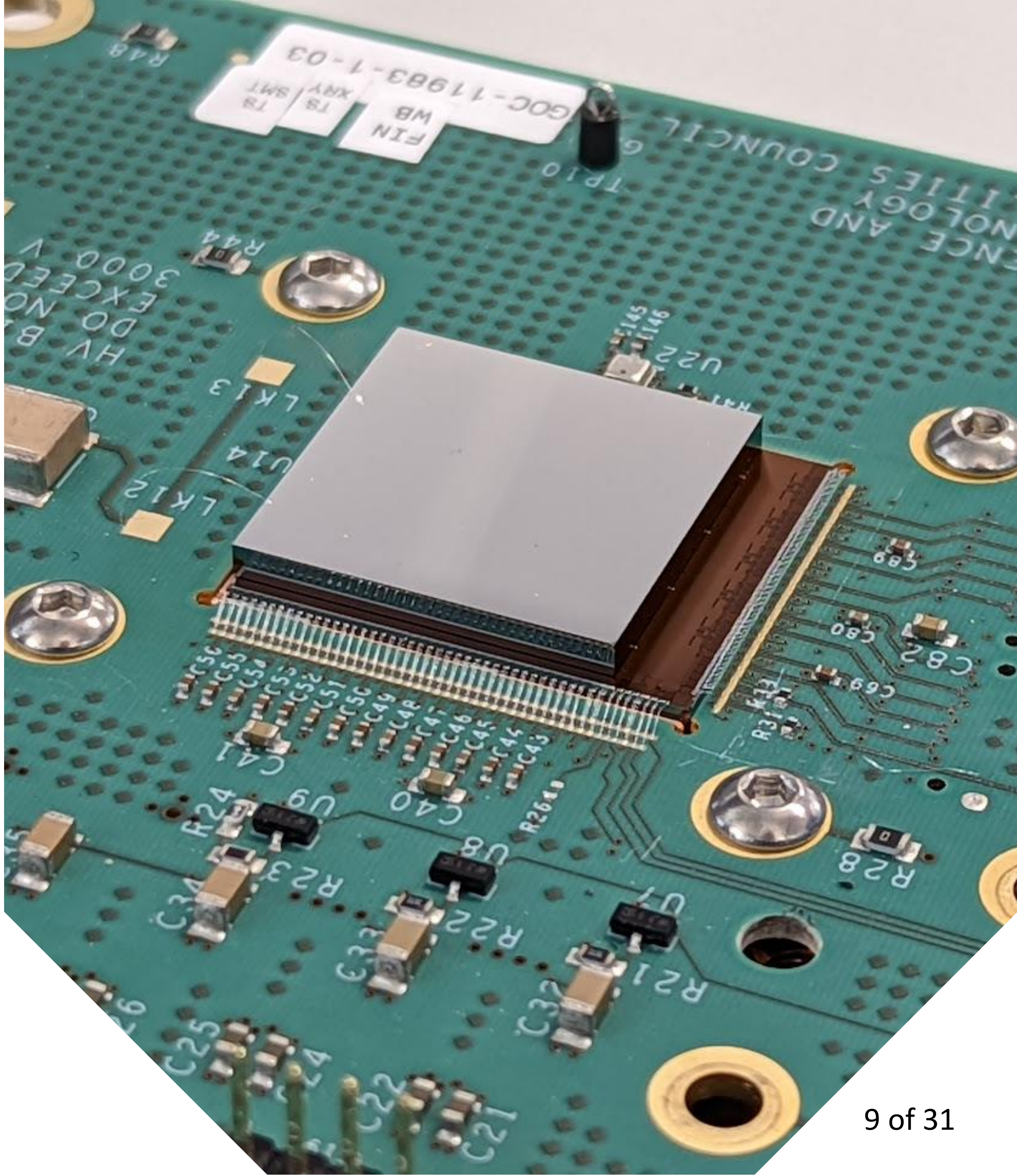
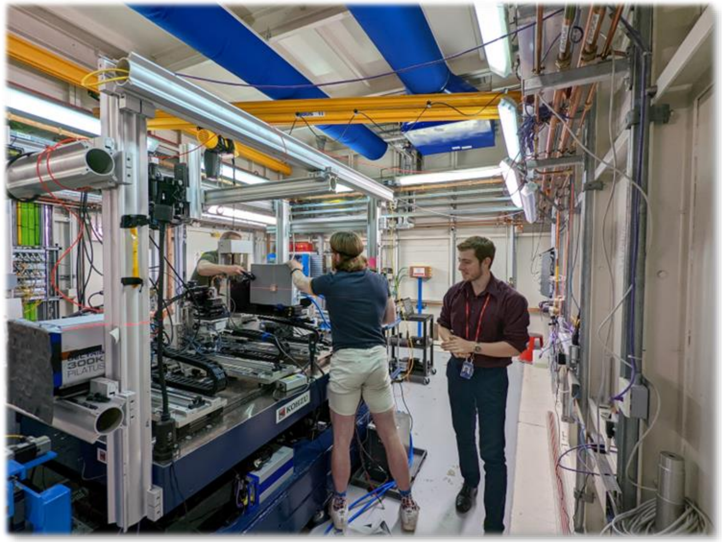
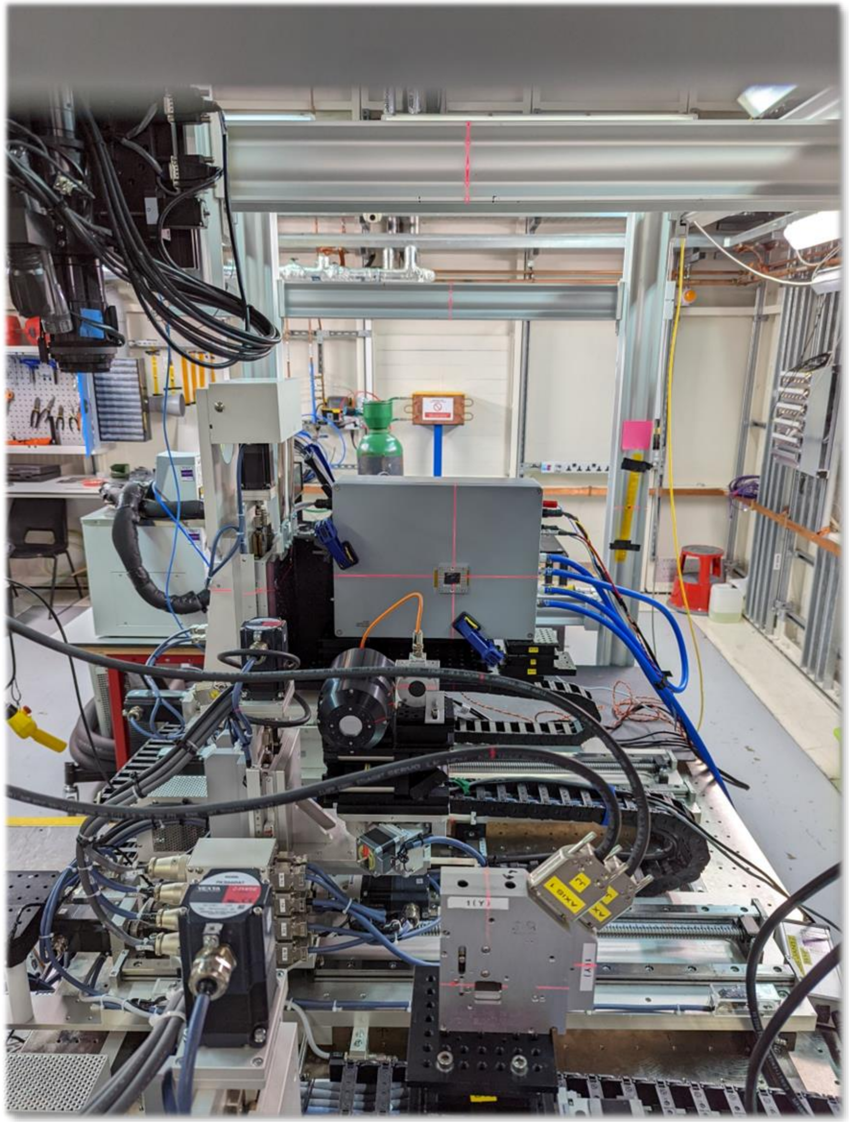


Experimentation at diamond

- **B16 Beamline: August 2022, December 2022, December 2023**
  - Monochromatic X-rays: 10 – 20 keV
  - Photon fluxes: **10^5 – 10^8 ph s^{-1} mm^{-2}**
  - 1 MHz data stream on one/four fast-data channels
  - Tested **HF-CZT (2 mm), p-type Si (300 µm), GaAs (500 µm)** devices

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





B16 setup photos

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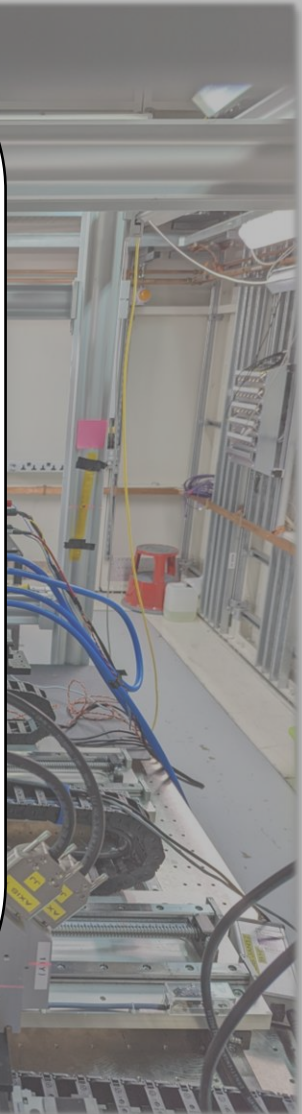
Experimentation at diamond

- **B16 Beamline**
  - Mono
  - Photo
  - 1 MH
  - Teste
- Beamline s



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Journal of Instrumentation

PAPER • OPEN ACCESS

Preliminary characterisation of the $HEXITEC_{MHz}$ spectroscopic X-ray imaging detector

M.C. Veale[1], S. Bell[1], B.D. Cline[1], I. Church[1], S. Cross[1], C. Day[1], M. French[1], T. Gardiner[1], N. Ghorbanian[1], M.D. Hart[1] + Show full author list

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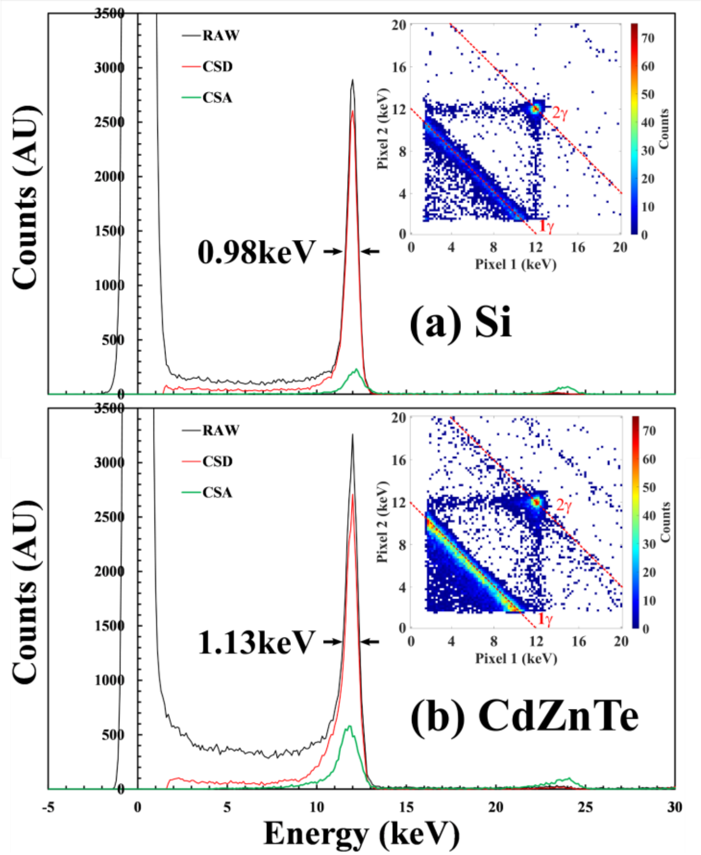
Journal of Instrumentation, Volume 18, July 2023

Citation M.C. Veale *et al* 2023 *JINST* 18 P07048

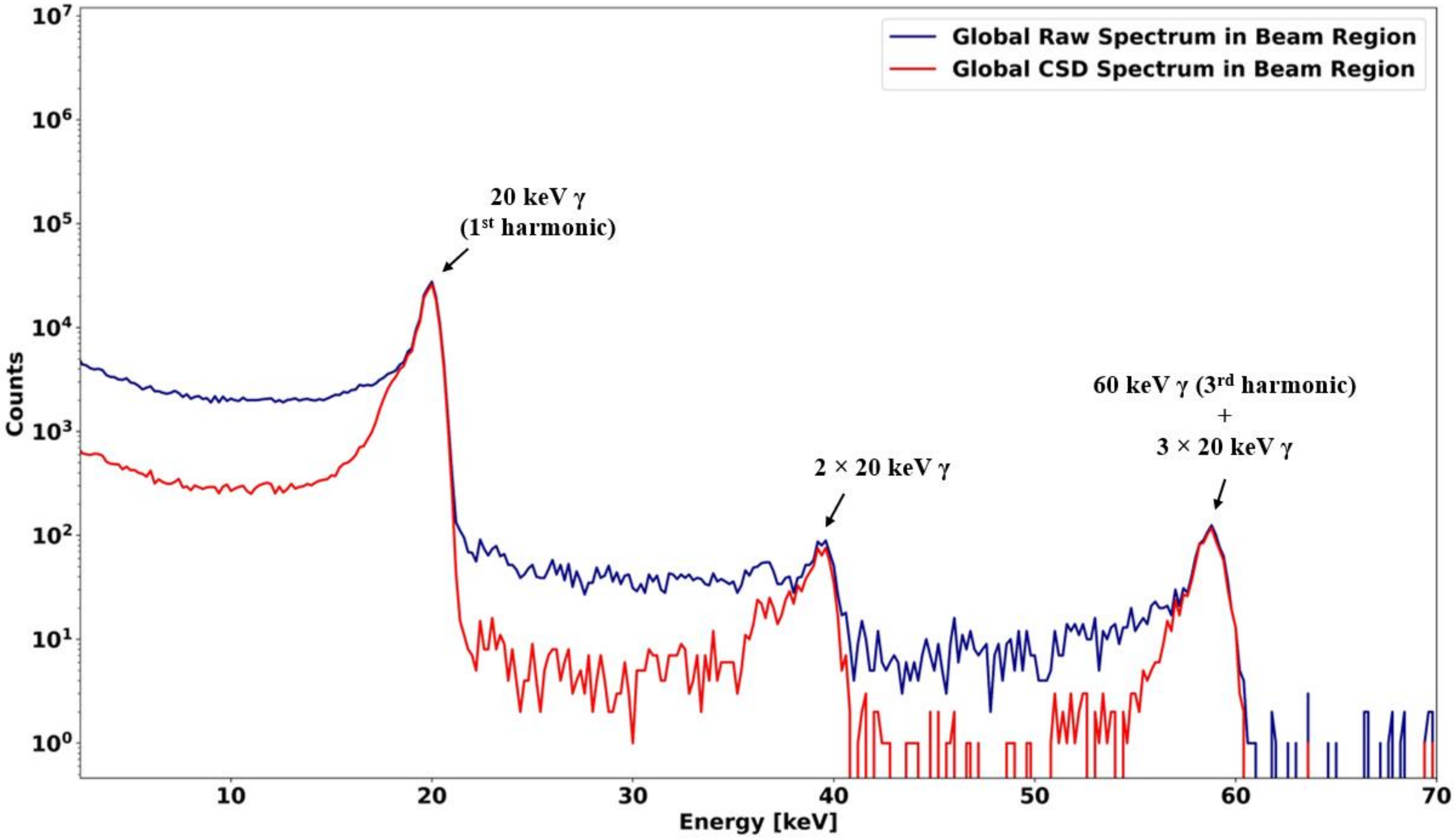
DOI: 10.1088/1748-0221/18/07/P07048



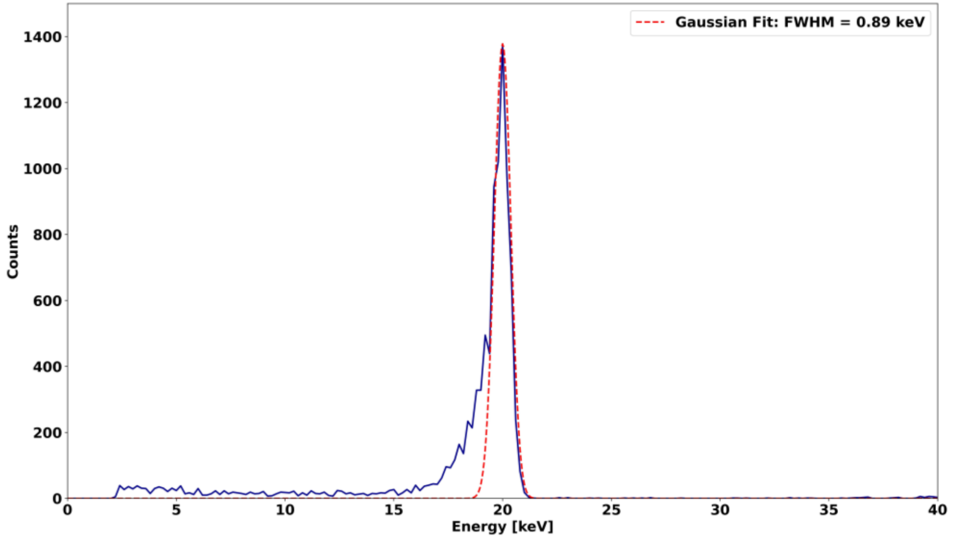
HF-CZT Spectroscopic Imaging Characterisation

Summary of 20 keV spectroscopic results (HG = High gain etc.)

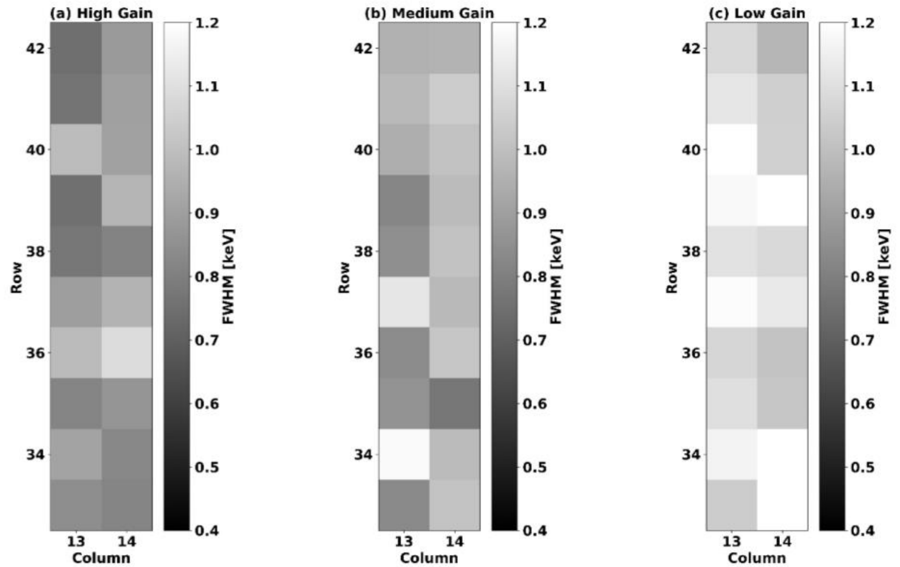
Energy (keV)	HG FWHM (keV)	MG FWHM (keV)	LG FWHM (keV)
20	0.85 ± 0.10	0.92 ± 0.11	1.13 ± 0.12



Calibrated raw and CSD spectra of illuminated pixels in an 8 mm Al 20 keV high-gain dataset (2.93×10^5 ph s^{-1} mm^{-2}) - 0.1 keV bin width



Pixel (13,37) high-gain CSD spectrum with Gaussian fit to the 20 keV photo peak - 0.2 keV bin width



20 keV FWHM distributions in the beam

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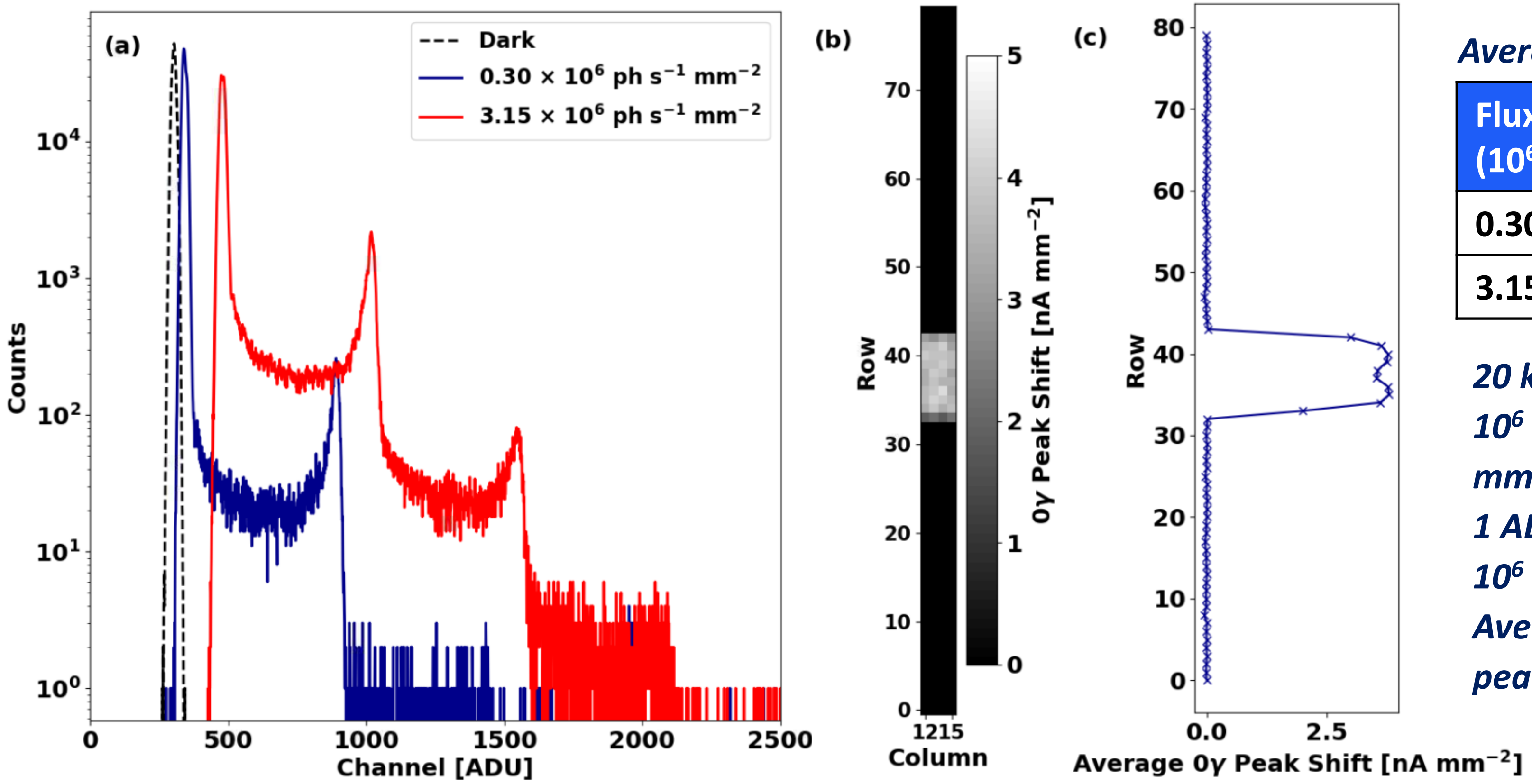
‘Excess Leakage Current Effect’ Identification - Comparing HF-CZT data at two fluxes



*Average results in beam**

Flux (10^6 ph s^{-1} mm^{-2})	Offset (ADU)	Offset (keV)	Offset (nA mm^{-2})
0.30	36 ± 7	1.31 ± 0.25	0.80 ± 0.15
3.15	160 ± 28	5.91 ± 1.05	3.60 ± 0.64

20 keV high-gain results at 0.30 × 10^6 ph s^{-1} mm^{-2} and 3.15 × 10^6 ph s^{-1} mm^{-2}. (a) Pixel (13,37) raw spectra – 1 ADU bin width. (b) Map of 3.15 × 10^6 ph s^{-1} mm^{-2} 0γ peak shifts. (c) Average 3.15 × 10^6 ph s^{-1} mm^{-2} 0γ peak shift across each readout row

$$* \text{ Shift } [A\ \text{mm}^{-2}] = \frac{\text{Shift } [ADU] \times (\text{ADU} - \text{keV conversion factor})}{\text{Integration time } \times (\text{CZT pair conversion energy}) \times \text{Pixel area}}$$

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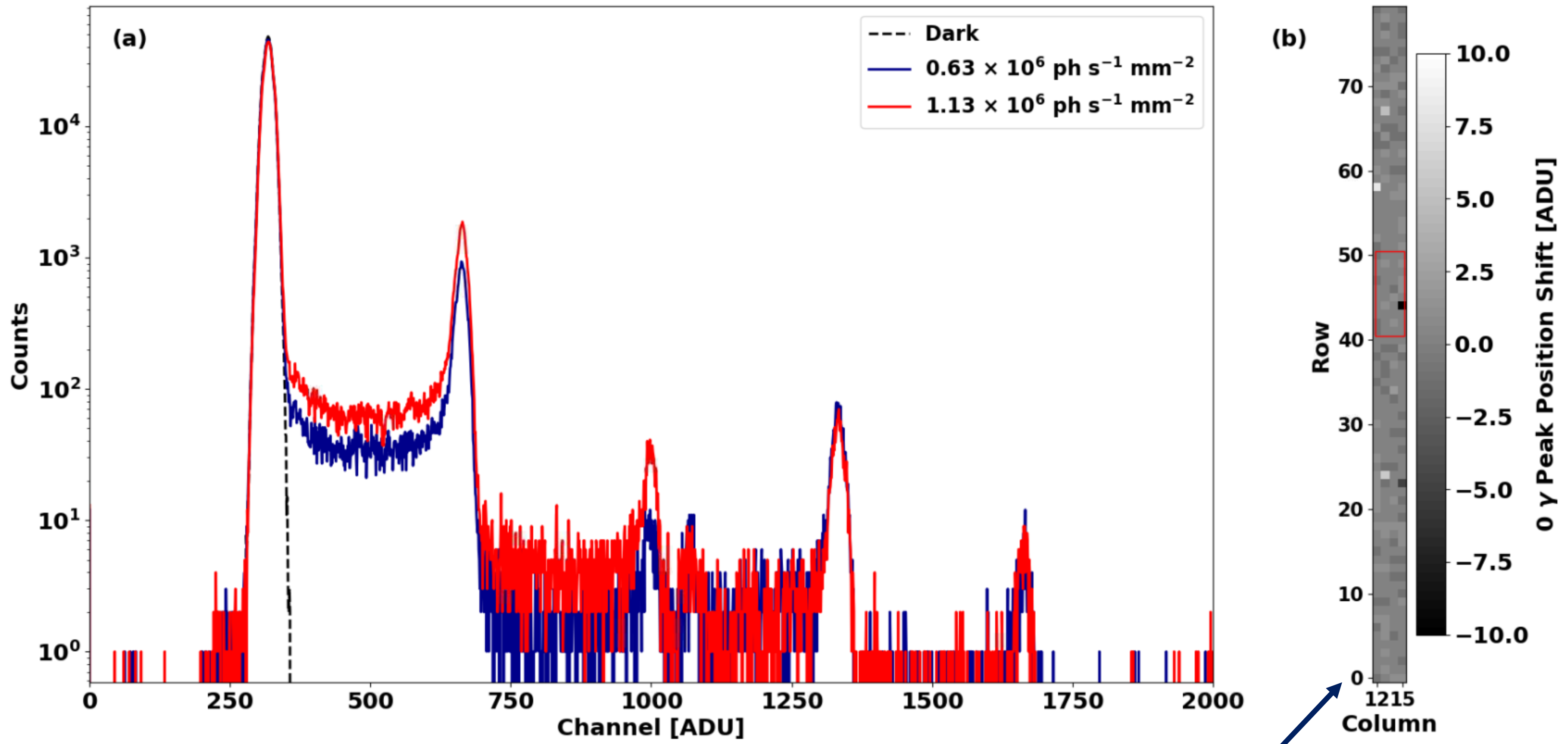
'Excess Leakage Current Effect' Identification - Comparing p-type Si data at two fluxes



<3 ADU shifts result of minor ASIC power-supply fluctuations

p-type Si FWHM results

Energy (keV)	HG FWHM (keV)	MG FWHM (keV)
10	0.66 ± 0.06	0.77 ± 0.10
15	0.68 ± 0.06	0.81 ± 0.10

10 keV p-type Si high-gain results at 0.63 × 10^6 ph s^{-1} mm^{-2} and 1.13 × 10^6 ph s^{-1} mm^{-2}. (a) Pixel (15,44) raw spectra – 1 ADU bin width. (b) Map of 1.13 × 10^6 ph s^{-1} mm^{-2} 0γ peak shifts. Beam position highlighted red

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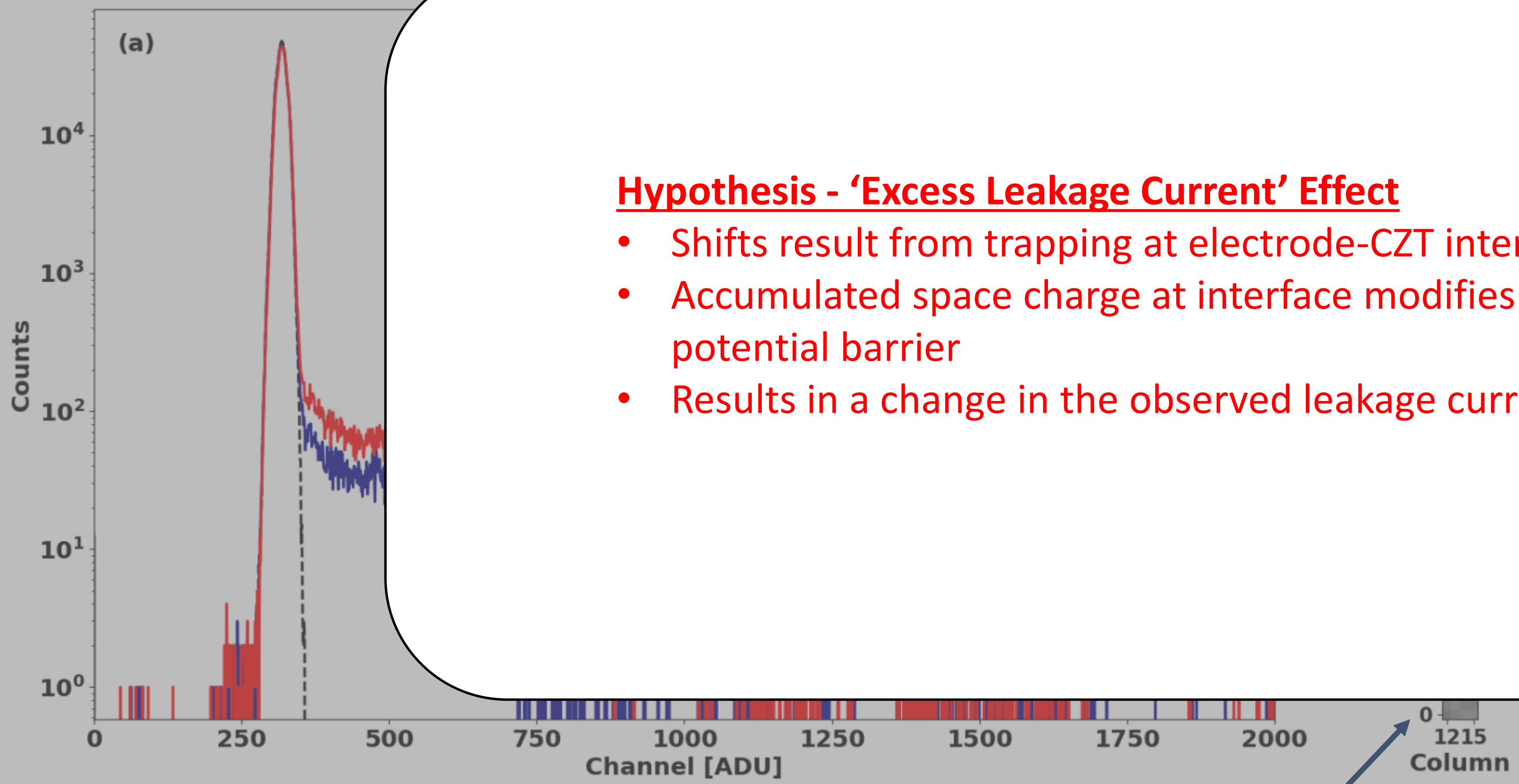
'Excess Leakage Current Effect' Identification - Comparing p-type Si data at two fluxes

p-type Si FWHM results

	HG FWHM (keV)	MG FWHM (keV)
	0.66 ± 0.06	0.77 ± 0.10
	0.68 ± 0.06	0.81 ± 0.10



Hypothesis - 'Excess Leakage Current' Effect

- Shifts result from trapping at electrode-CZT interface
- Accumulated space charge at interface modifies the potential barrier
- Results in a change in the observed leakage current

-type Si high-gain results
10^6 ph s^{-1} mm^{-2} and 1.13 ×
mm^{-2}. (a) Pixel (15,44)
tra – 1 ADU bin width. (b)
1.13 × 10^6 ph s^{-1} mm^{-2} 0γ
peak shifts. Beam position
highlighted red

<3 ADU shifts result of minor ASIC power-supply fluctuations

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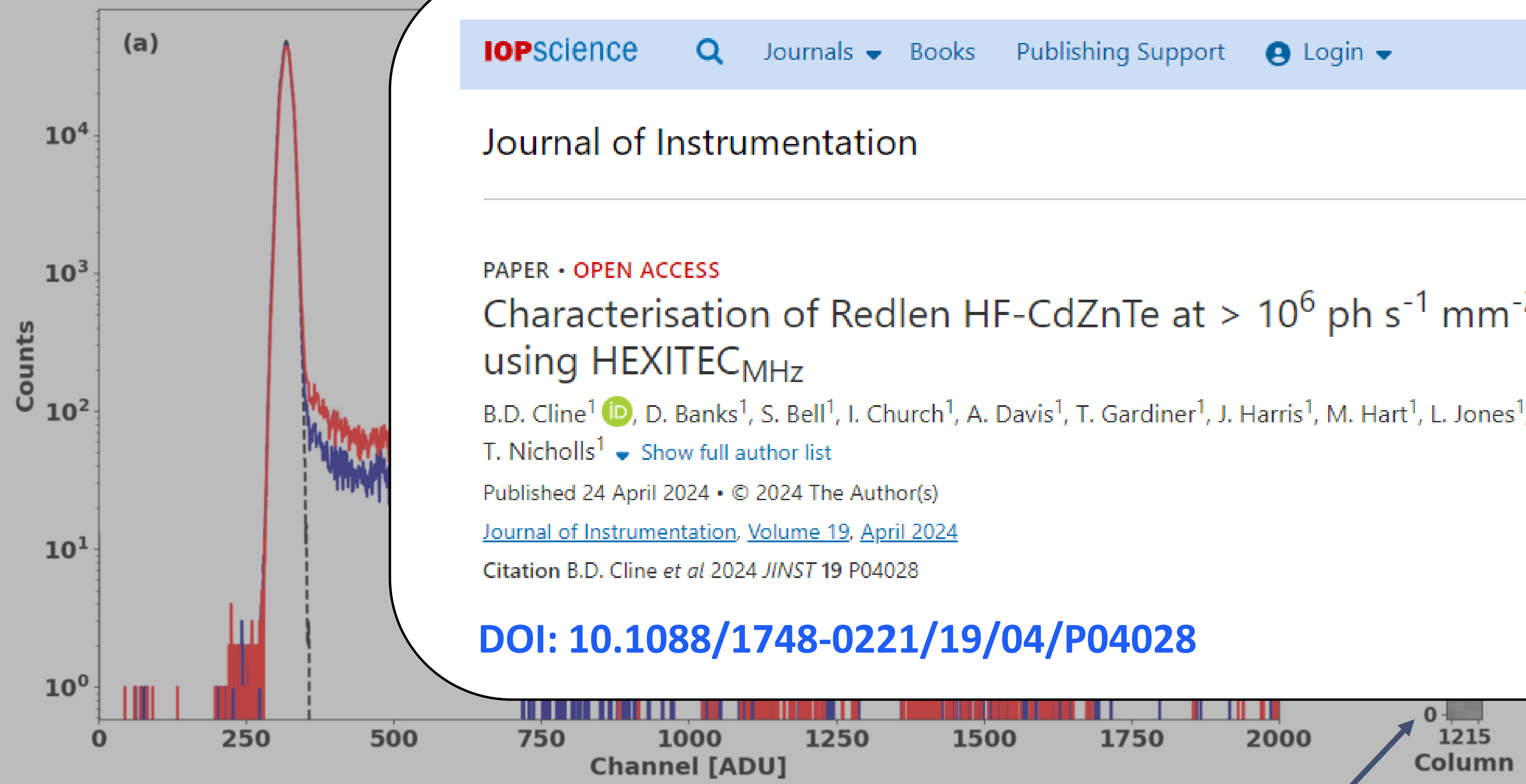
‘Excess Leakage Current Effect’ Identification - Comparing p-type Si data at two fluxes



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Journal of Instrumentation

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B.D. Cline[1], D. Banks[1], S. Bell[1], I. Church[1], A. Davis[1], T. Gardiner[1], J. Harris[1], M. Hart[1], L. Jones[1], T. Nicholls[1] Show full author list

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Citation B.D. Cline et al 2024 JINST 19 P04028

DOI: 10.1088/1748-0221/19/04/P04028

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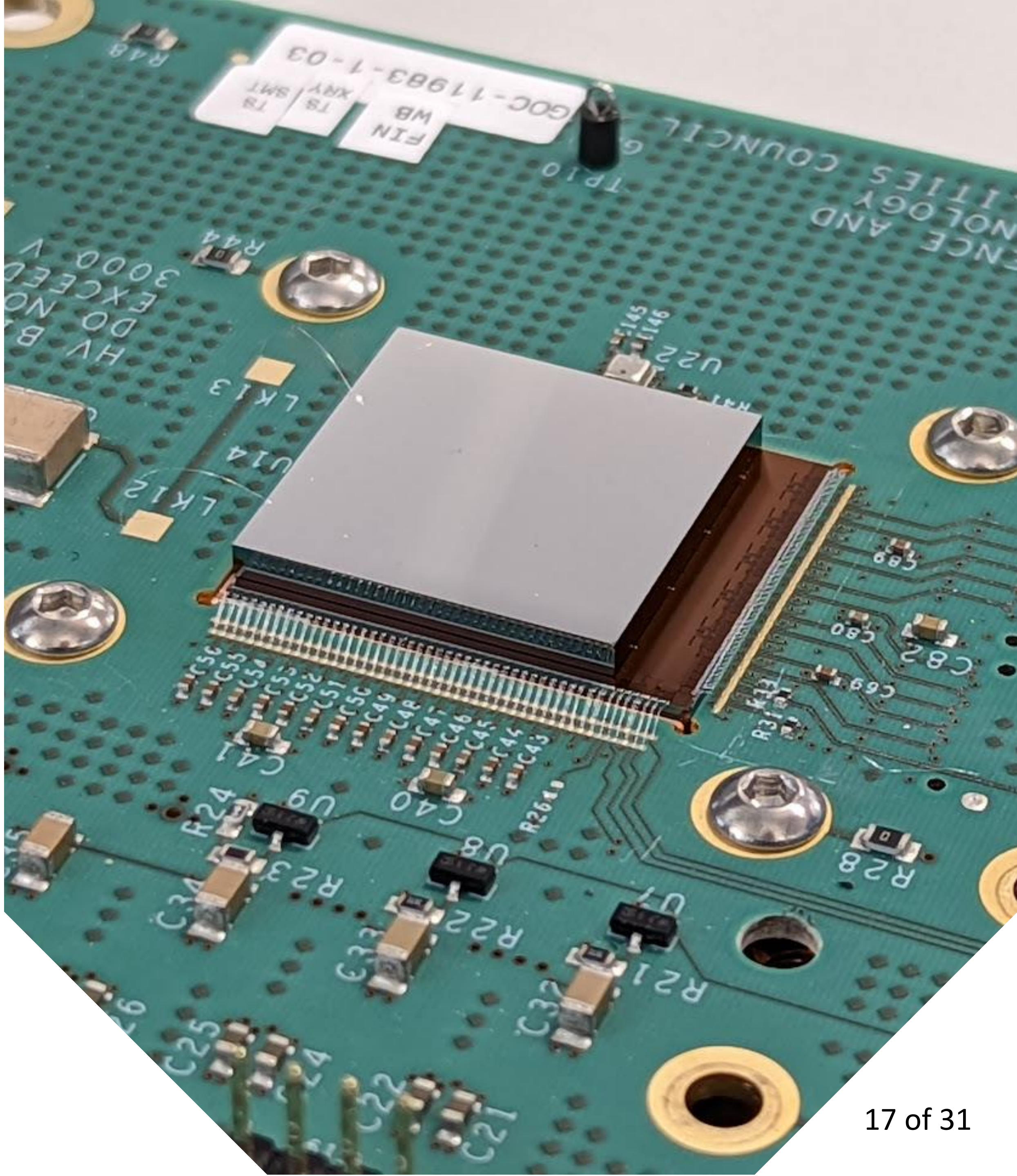

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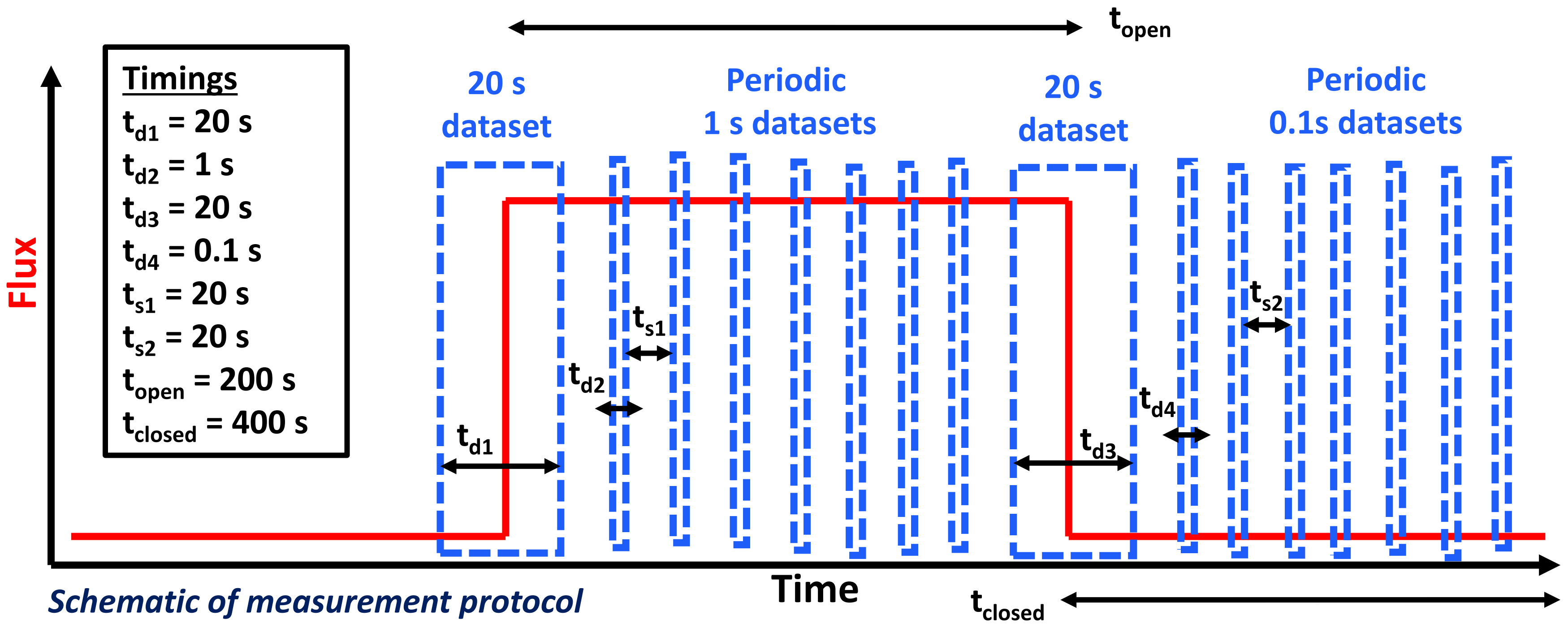
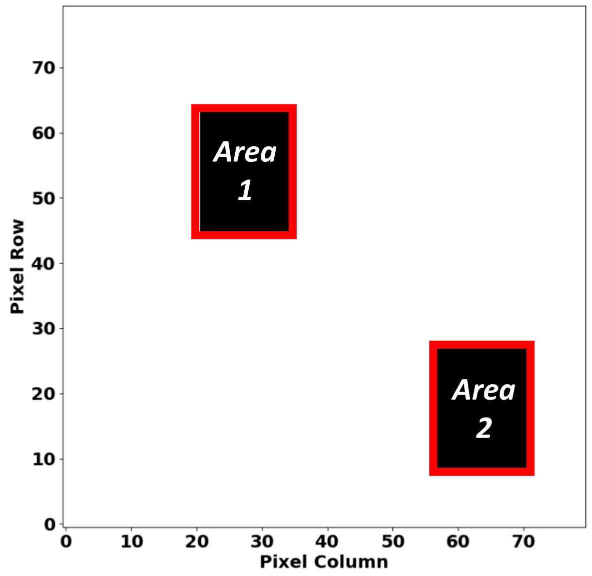
Format of Dynamic Datasets

- Dynamic datasets taken under specific conditions to further characterise ‘excess leakage current’ effect



Schematic of measurement protocol



Areas investigated

Variables investigated

Variable	Values
Energy (keV)	12, 20
Incident Flux (10^6 ph s^{-1} mm^{-2})	0.3, 1.2, 3.1, 7.8
Sensor Temperature (°C)	2.5,10,20,30,40,50
Sensor Bias Voltage (-V)	500,750,1000

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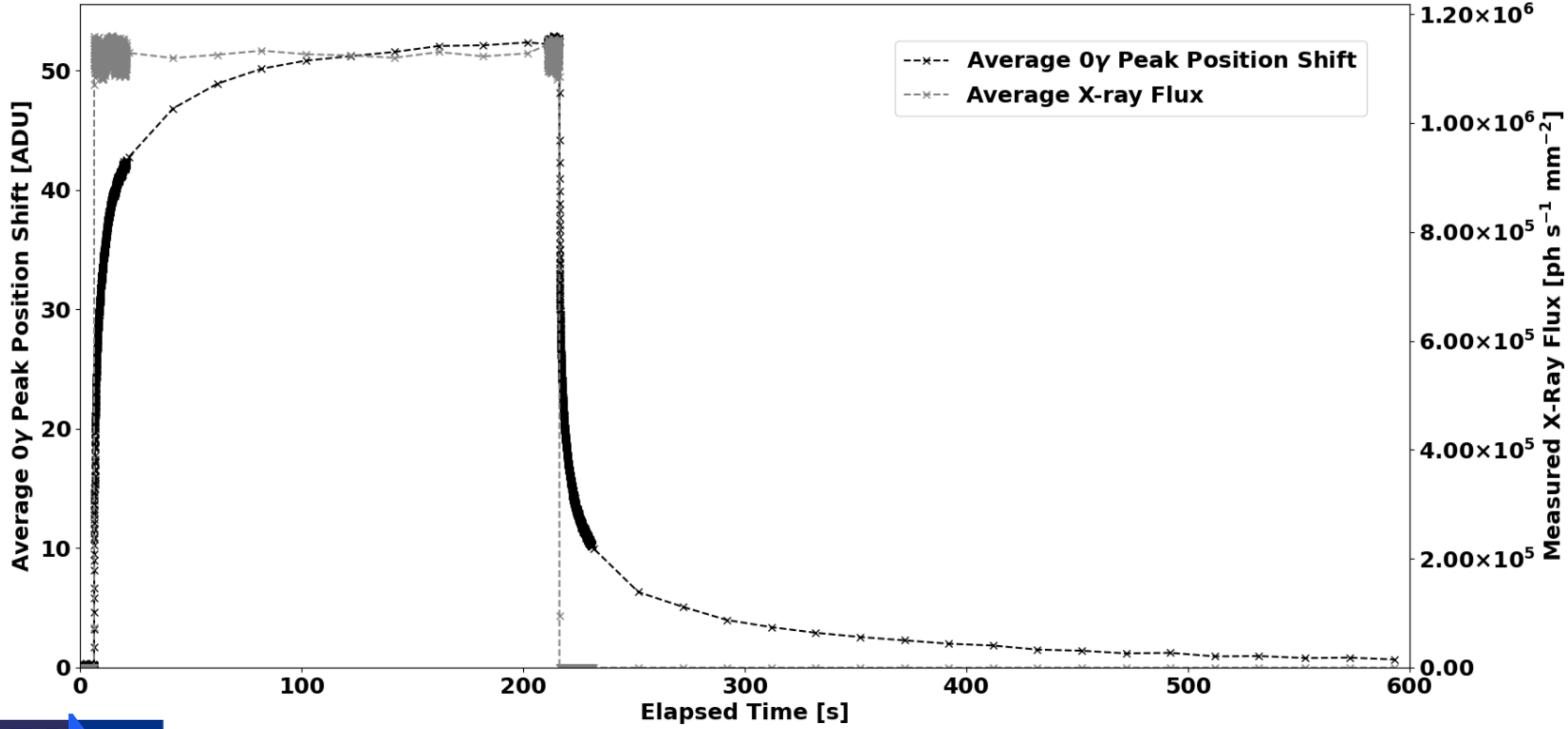
Example Dataset Results

Parameter	Energy	Gain	Flux	Temp	Bias
Value	20 keV	High	1.2×10^6 ph s^{-1} mm^{-2}	20 °C	-1000 V



Evolution of average 0γ peak shift and X-ray flux – 10^4 frame sampling window

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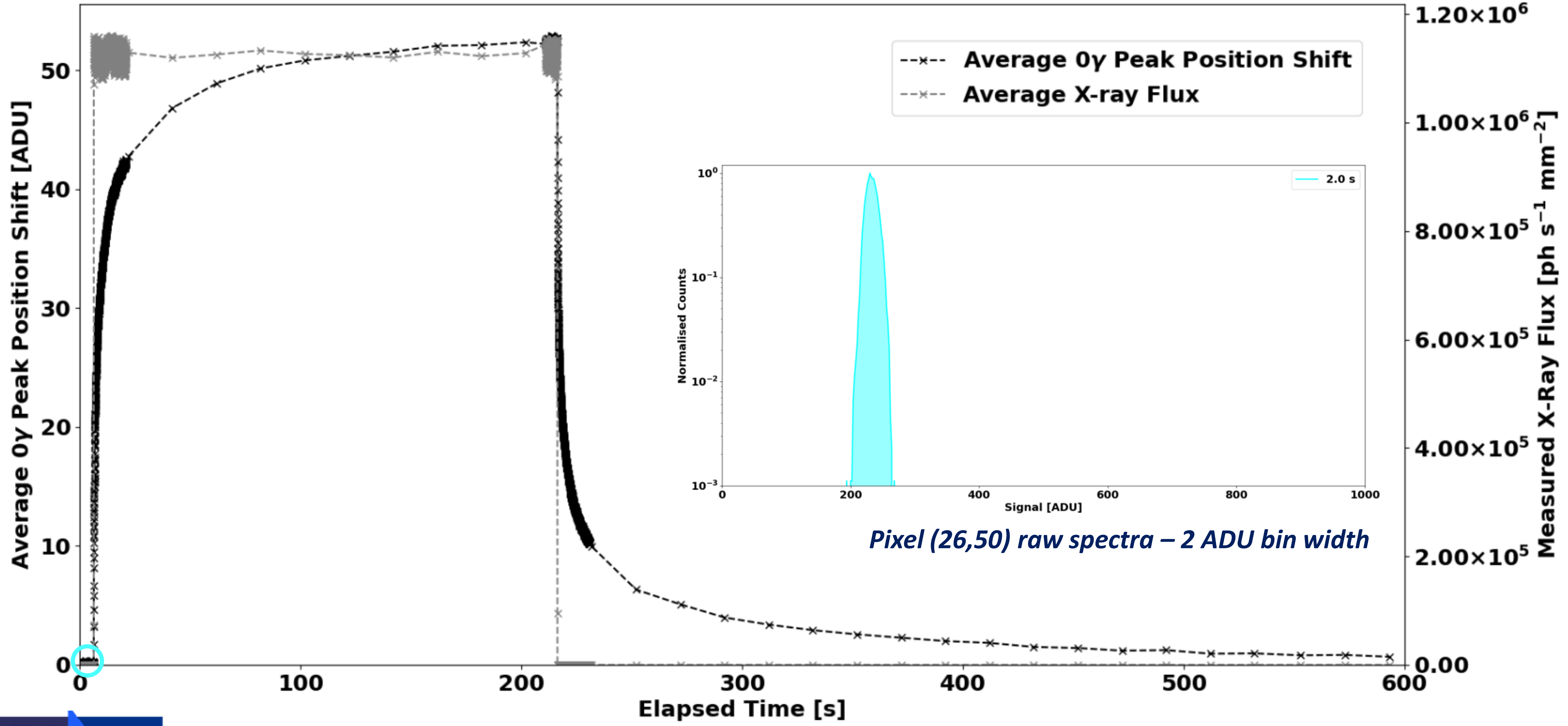
Example Dataset Results

Parameter	Energy	Gain	Flux	Temp	Bias
Value	20 keV	High	1.2×10^{6} ph s^{-1} mm^{-2}	20 °C	-1000 V



Pixel (26,50) raw spectra – 2 ADU bin width

Evolution of average 0γ peak shift and X-ray flux – 10^{4} frame sampling window

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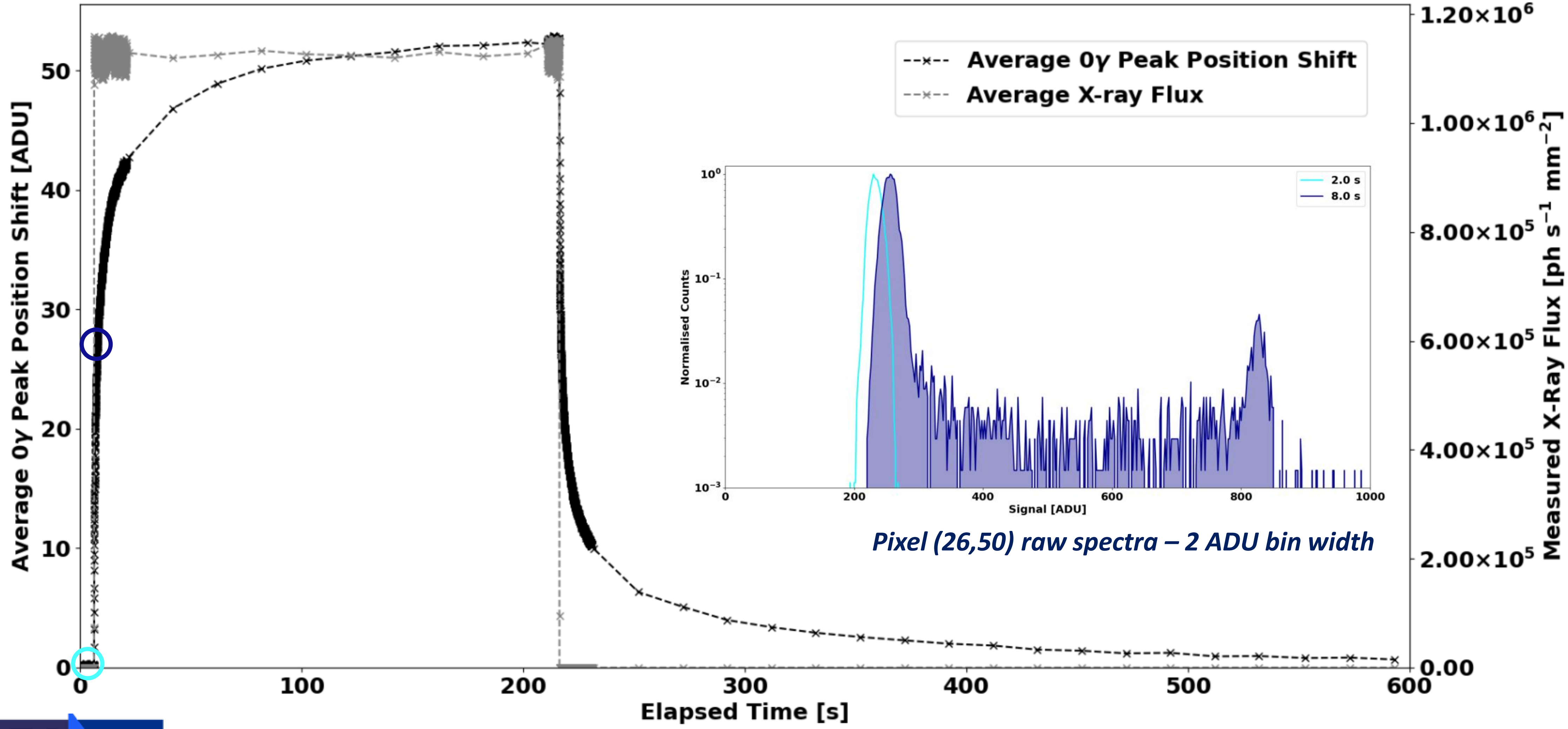
Example Dataset Results

Parameter	Energy	Gain	Flux	Temp	Bias
Value	20 keV	High	1.2×10^6 ph s^{-1} mm^{-2}	20 °C	-1000 V



Pixel (26,50) raw spectra – 2 ADU bin width

Evolution of average 0γ peak shift and X-ray flux – 10^4 frame sampling window

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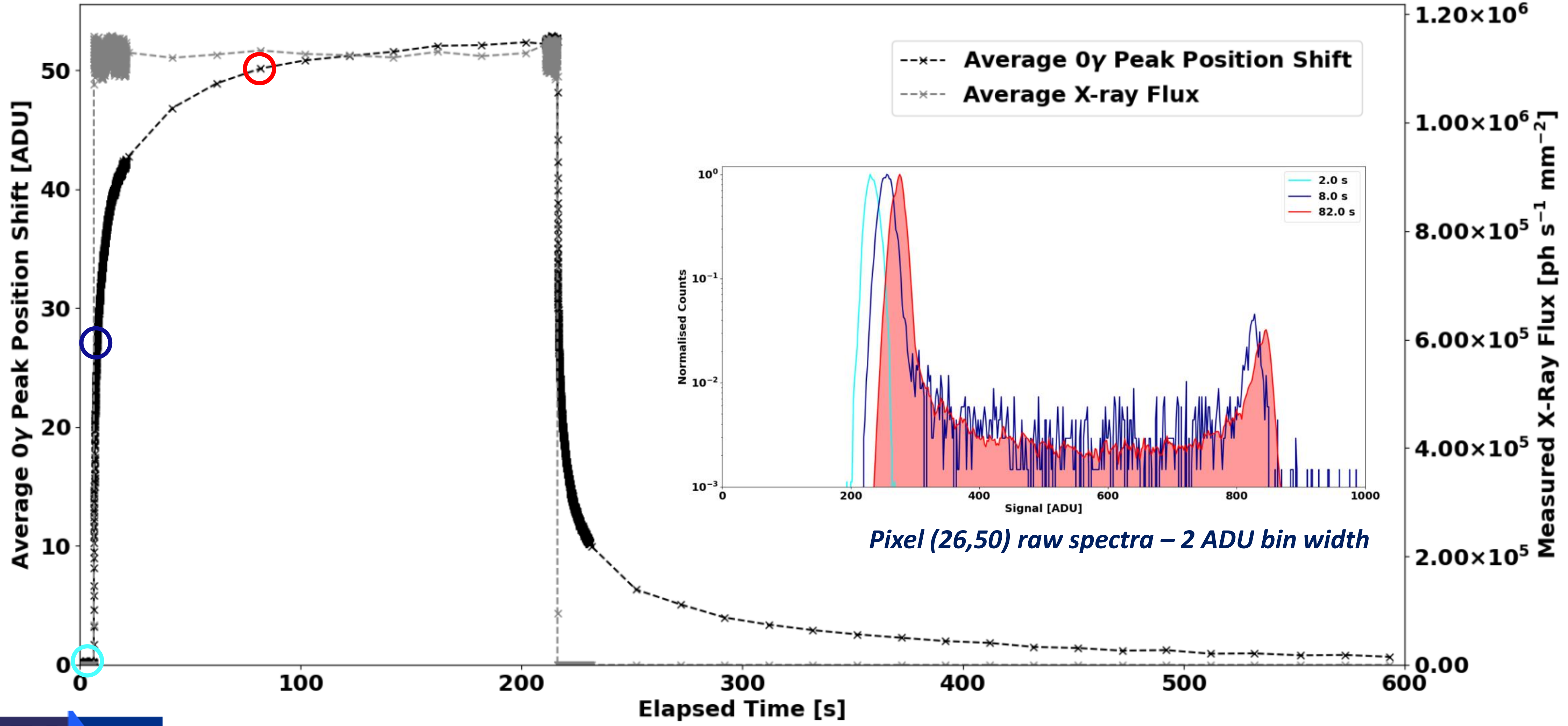
Example Dataset Results

Parameter	Energy	Gain	Flux	Temp	Bias
Value	20 keV	High	1.2×10^6 ph s^{-1} mm^{-2}	20 °C	-1000 V



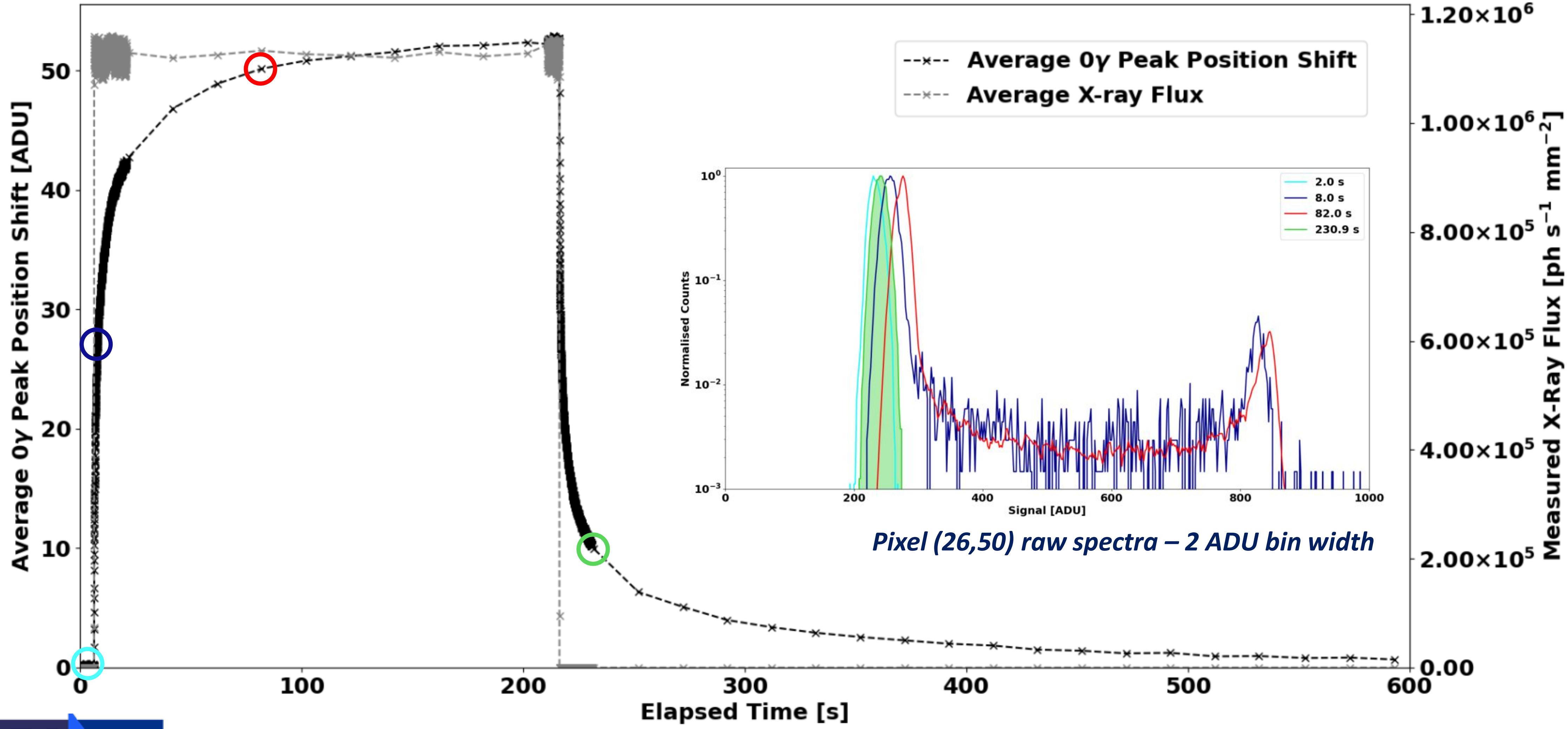
Pixel (26,50) raw spectra – 2 ADU bin width

Evolution of average 0γ peak shift and X-ray flux – 10^4 frame sampling window

Science and Technology Facilities Council

Example Dataset Results

Parameter	Energy	Gain	Flux	Temp	Bias
Value	20 keV	High	1.2×10^6 ph s^{-1} mm^{-2}	20 °C	-1000 V



Evolution of average 0γ peak shift and X-ray flux – 10^4 frame sampling window

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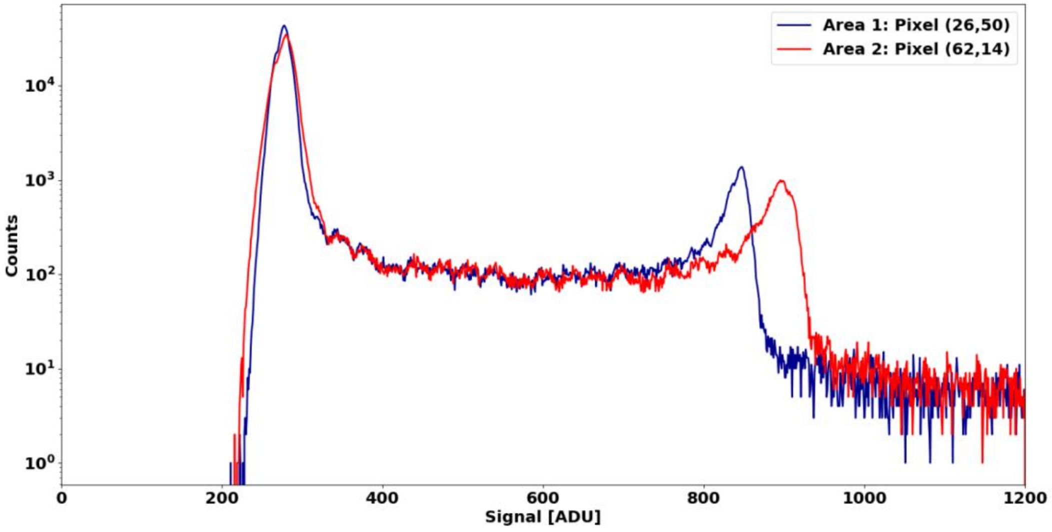
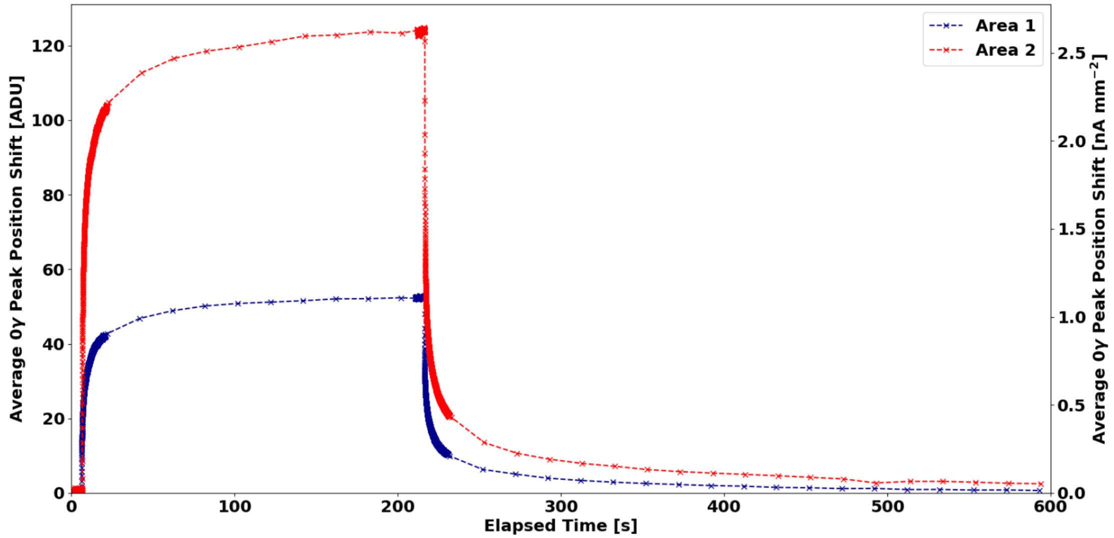
Spatial Dependency

Fixed Param	Energy	Gain	Flux	Temp	Bias
Value	20 keV	High	1.2×10^6 ph s^{-1} mm^{-2}	20 °C	-1000 V



Raw histograms at t ≈ 200 s – 1 ADU bin width

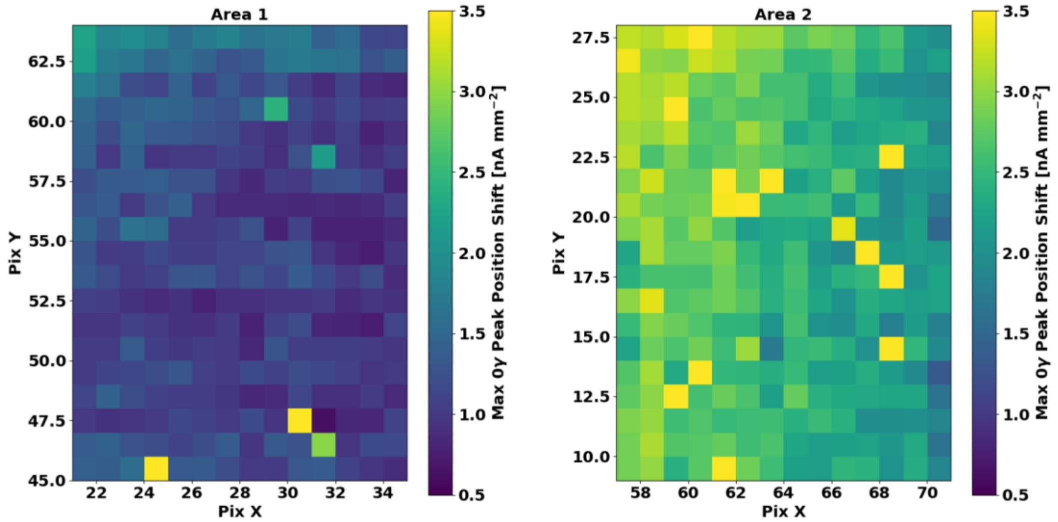


Average 0γ peak position shift in the beam region

Average shifts in the ROI*

Area	Shift (ADU)	Shift (nA mm^{-2})
1	51 ± 17	1.1 ± 0.4
2	121 ± 21	2.4 ± 0.4

****250 ADU threshold limit used for statistics***



Max 0γ peak position shift in the ROI

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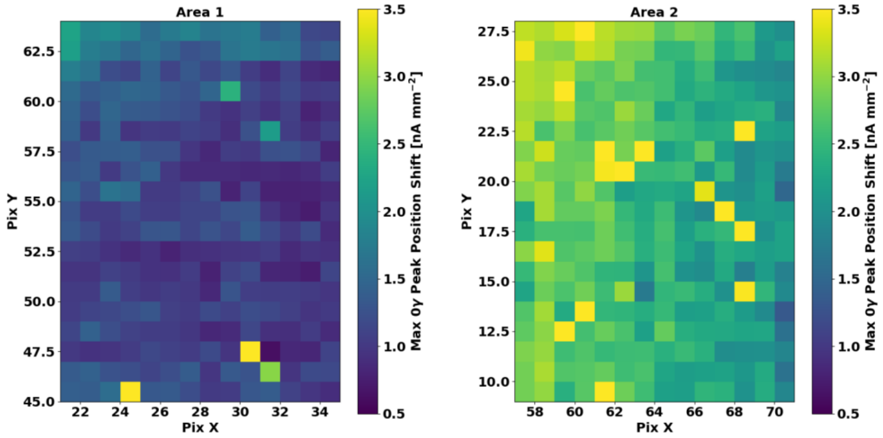
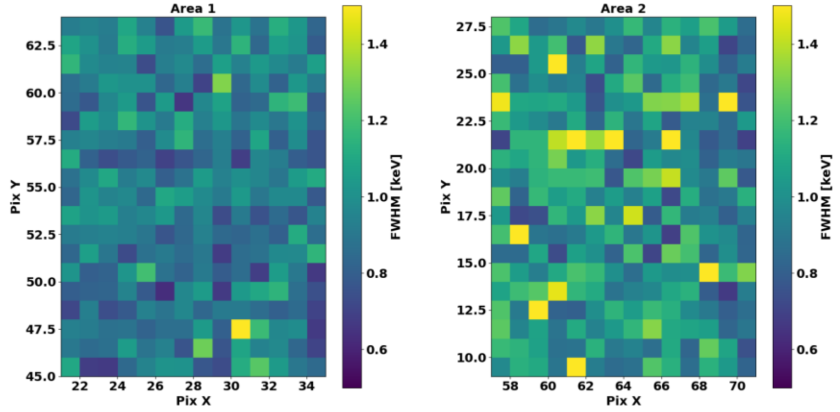
Spatial Dependency

Fixed Param	Energy	Gain	Flux	Temp	Bias
Value	20 keV	High	1.2×10^6 ph s^{-1} mm^{-2}	20 °C	-1000 V

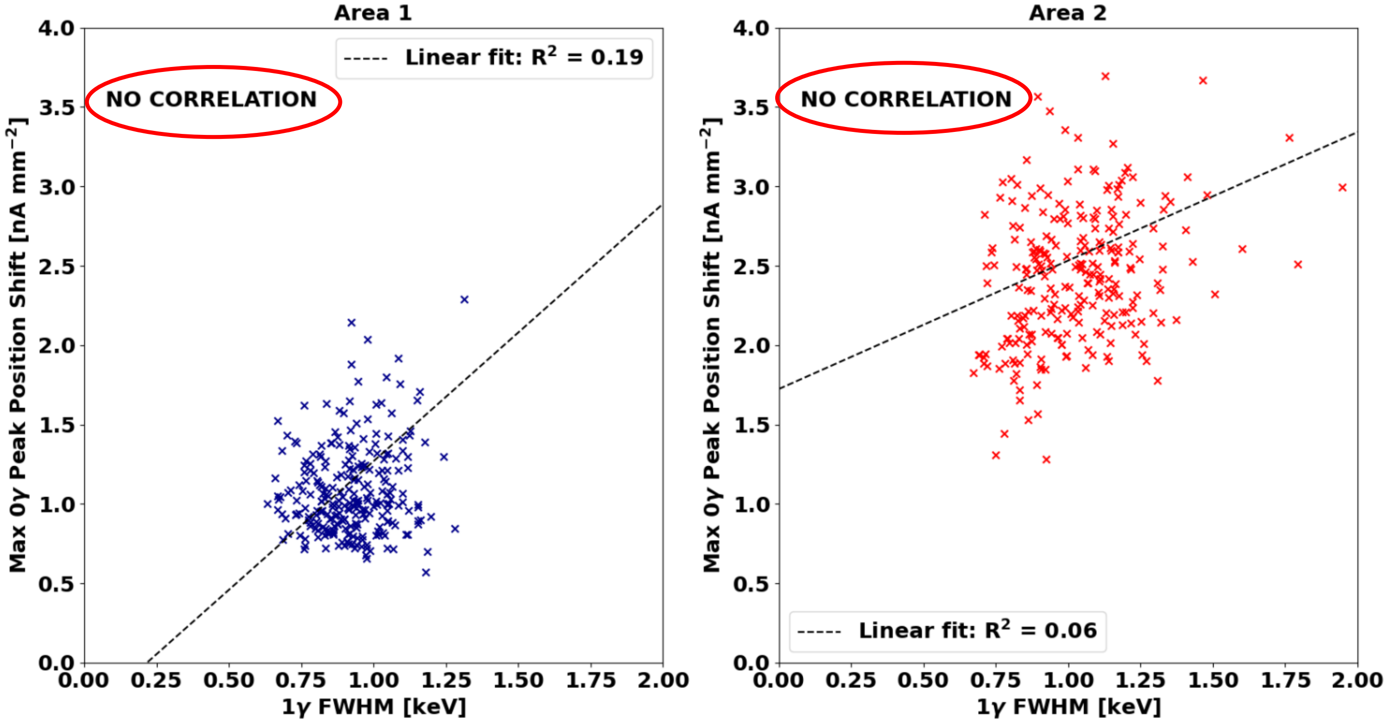
For comparison:



Max 0γ peak position shift in the ROI



1γ FWHM in the ROI



Mapping max 0γ peak shifts against the 1γ FWHM

- Photo peak **FWHM dictated by bulk properties**
- **No correlation in fits** of 0γ peak shifts against 1γ photo peak FWHM
  - Suggests **excess current dictated by interface properties**

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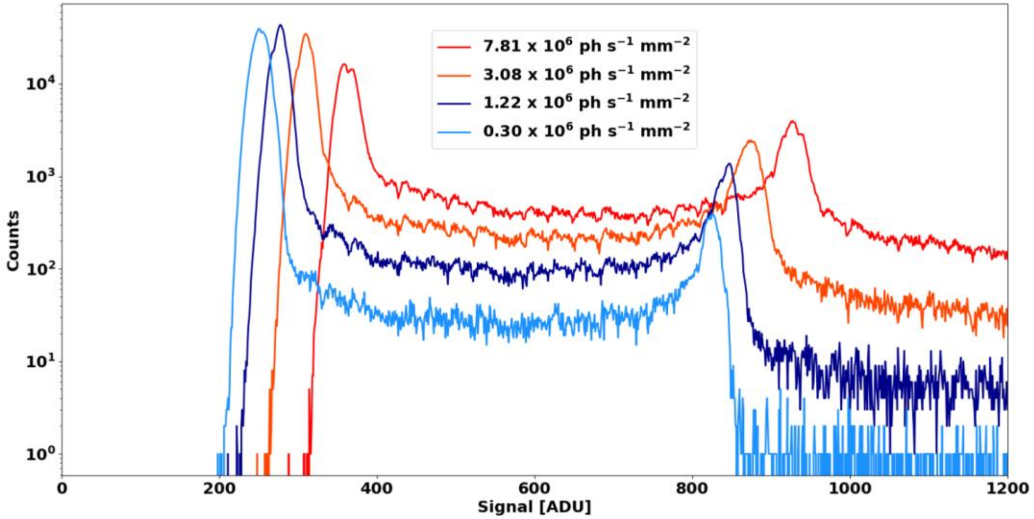
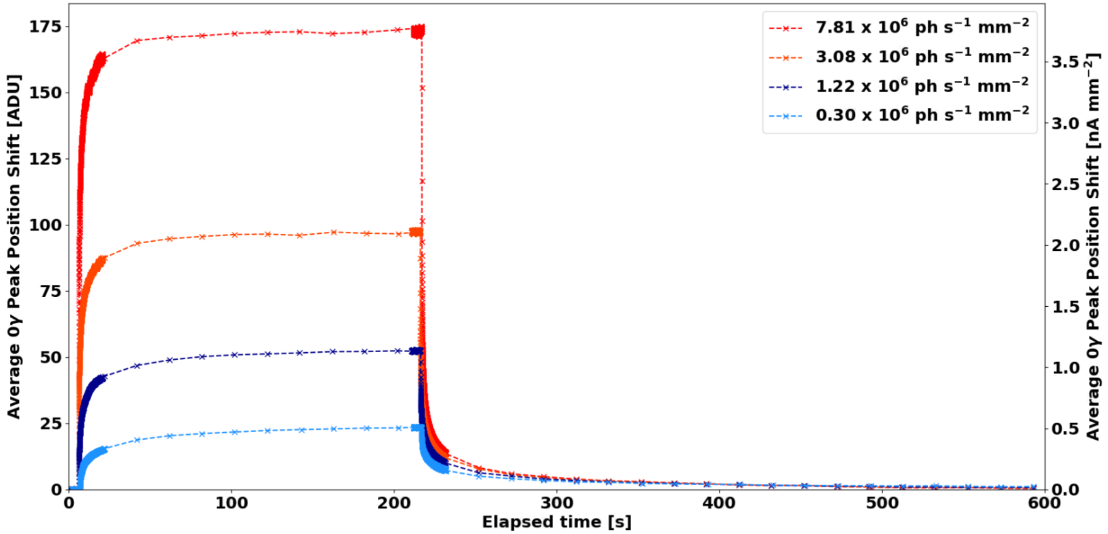
Flux dependency

Fixed Param	Energy	Gain	Temp	Bias
Value	20 keV	High	20 °C	-1000 V



Pixel (26,50) raw histograms at t ≈ 200 s – 1 ADU bin width

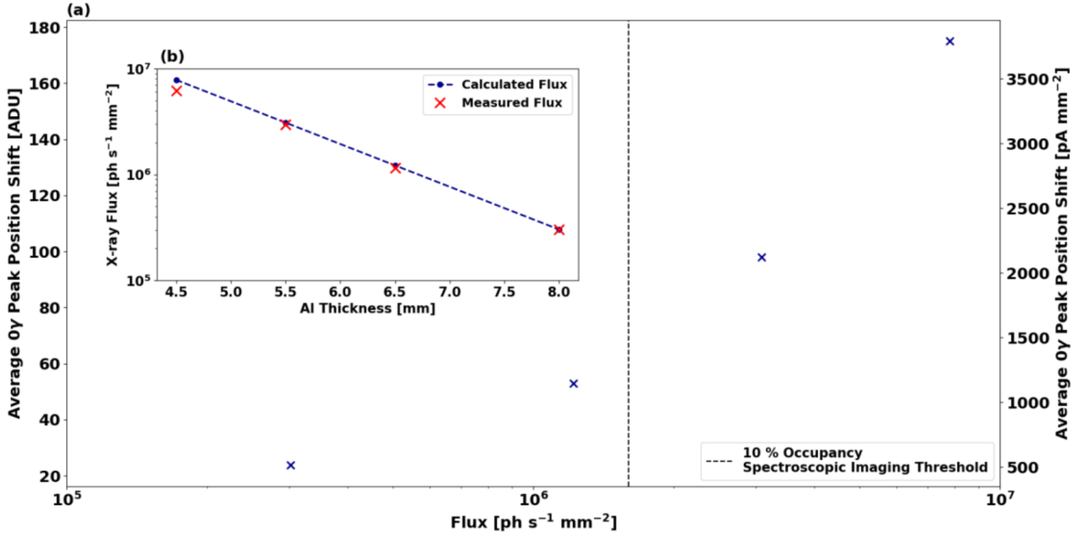


Average 0γ peak shift in the beam

Average 0γ peak position shift decay times

Flux (10^6 ph s^{-1} mm^{-2})	Decay time to 15 ADU (s)*
0.30	0.91
1.22	5.59
3.08	9.42
7.81	12.20

**15 ADU chosen as ~0.5 keV (~resolution of $HEXITEC_{MHz}$)*



(a) 0γ peak shift at calculated fluxes. (b) Comparison of calculated and measured fluxes

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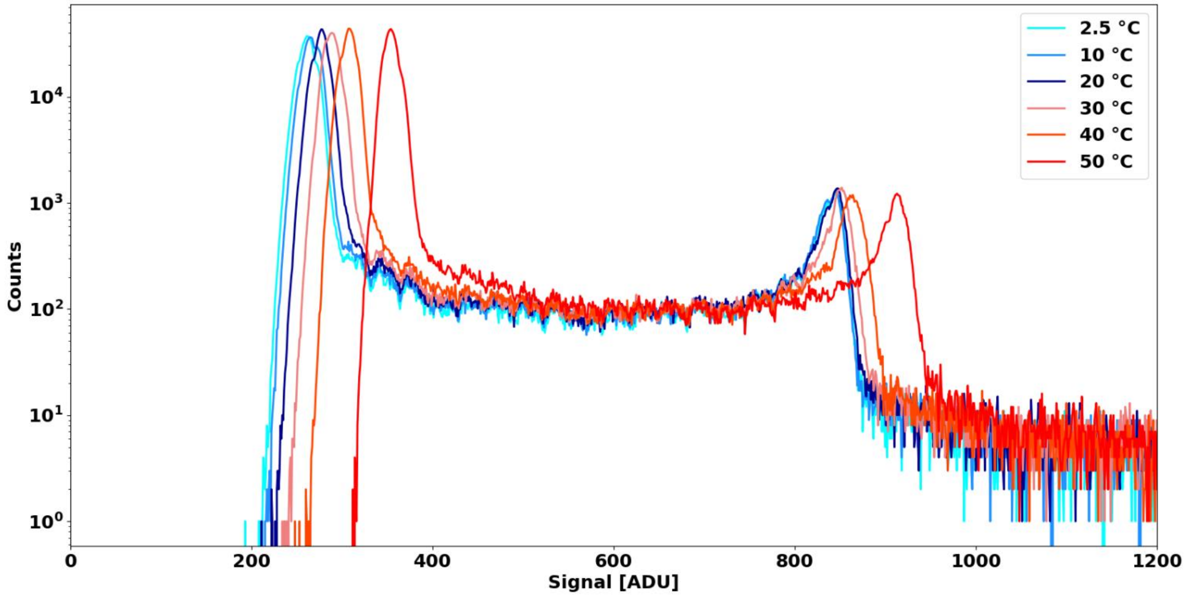
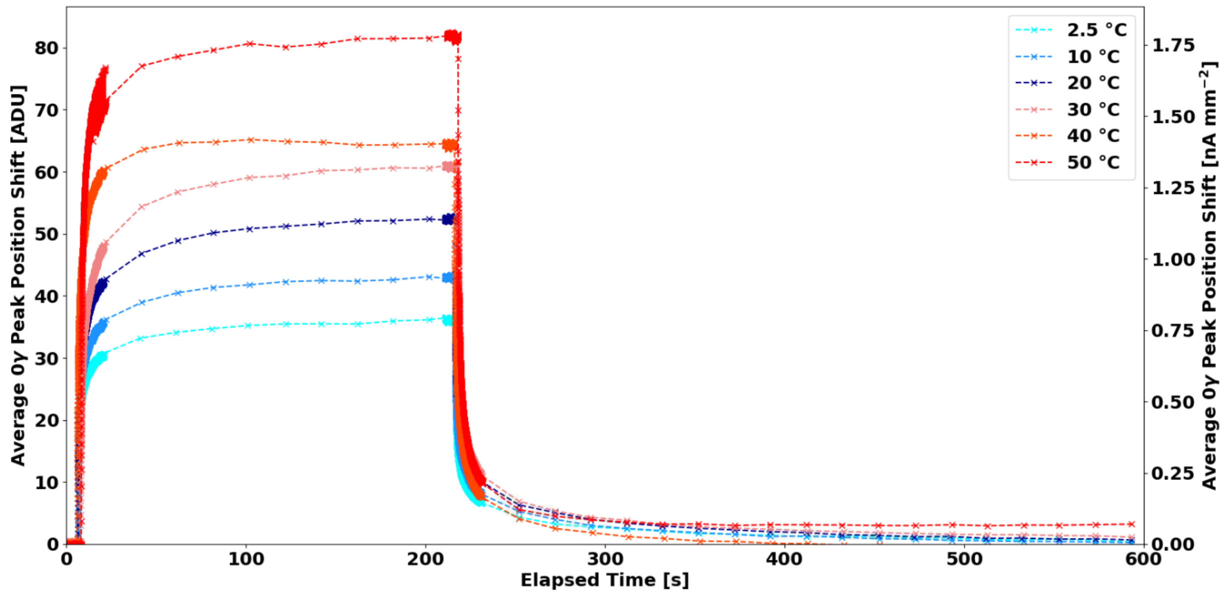
Temperature dependency

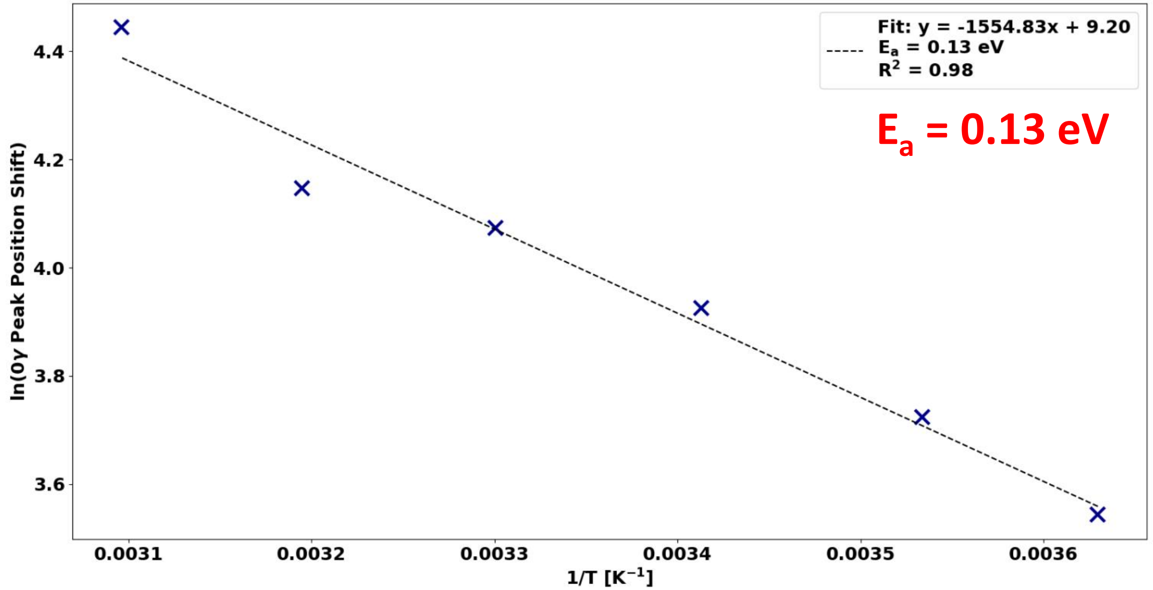
Fixed Param	Energy	Gain	Flux	Bias
Value	20 keV	High	1.2×10^6 ph s^{-1} mm^{-2}	-1000 V



Pixel (26,50) raw histograms at t ≈ 200 s – 1 ADU bin width



Average 0γ peak position shift in the beam



Arrhenius Analysis

- **0.13 eV E_a** associated with well-known CZT defect
  - A-centres generated by **Indium doping**

Agenda

1 $\text{HEXITEC}_{\text{MHz}}$ Overview

The next generation of HEXITEC systems

2 Redlen HF-CZT Overview

CdZnTe for use at high X-ray fluxes ($<10^{9}$ ph s^{-1} mm^{-2})

3 Initial HF-CZT Test Results

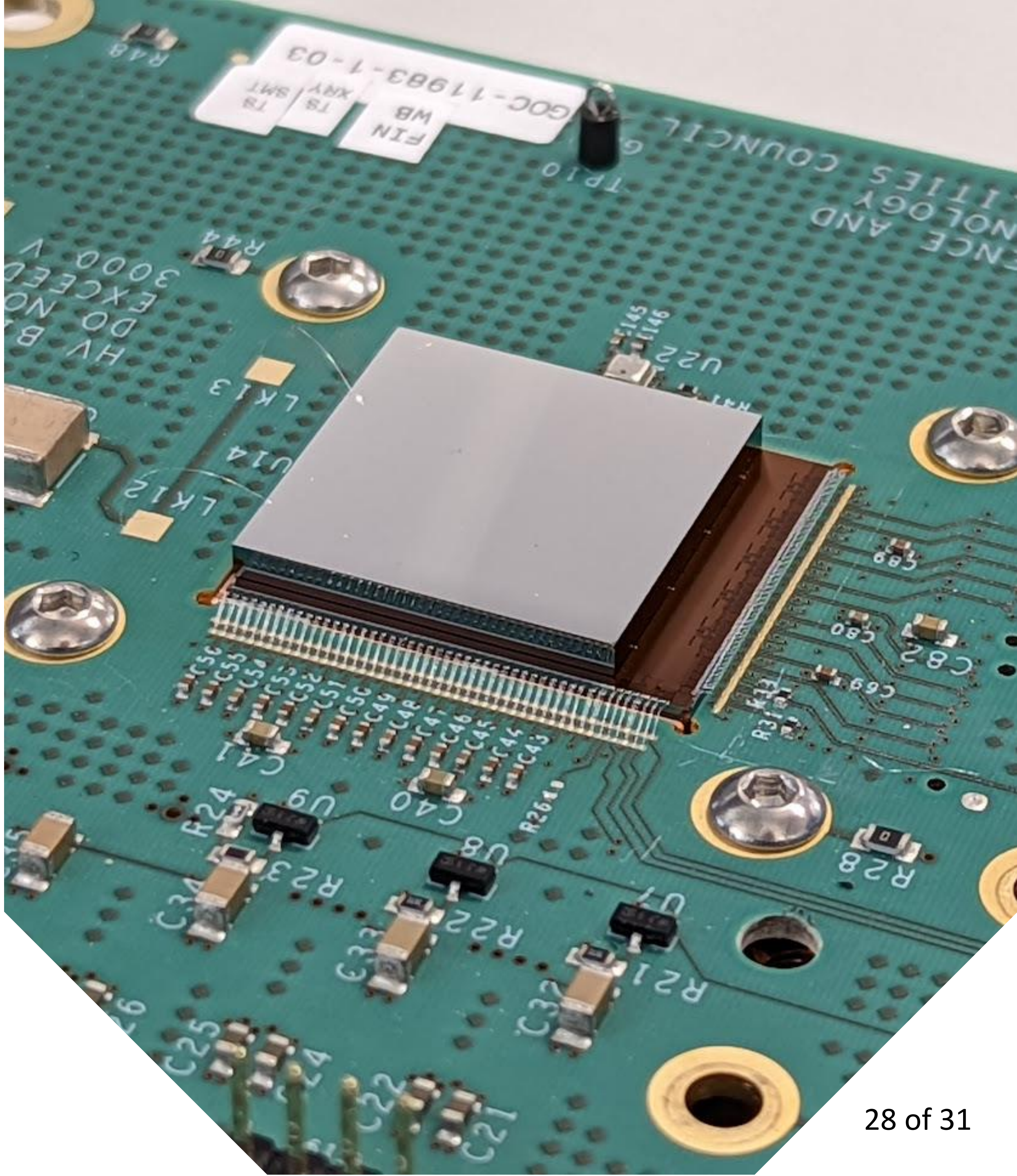
Results from HF-CZT characterisation carried out at the DLS B16 Test Beamline in December 2022

4 Recent HF-CZT Test Results

Results from HF-CZT characterisation carried out at the DLS B16 Test Beamline in December 2023

5 Next Steps

Future Work planned



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Next Steps

Testing and delivery of new DAQ system

- Verification of 80 × 80 output, in-FPGA dark-correction and histogramming
- Will enable lab-based analysis of effect using lower-flux sealed sources

ESRF beamtime (Jul 2024) ≤75 keV

- Temperature-dependency of ‘excess leakage current’ effect
  - Further Arrhenius analysis
  - PICTS analysis of $\text{HEXITEC}_{\text{MHz}}$ data

DLS B16 beamtime (Dec 2024) ≤20 keV

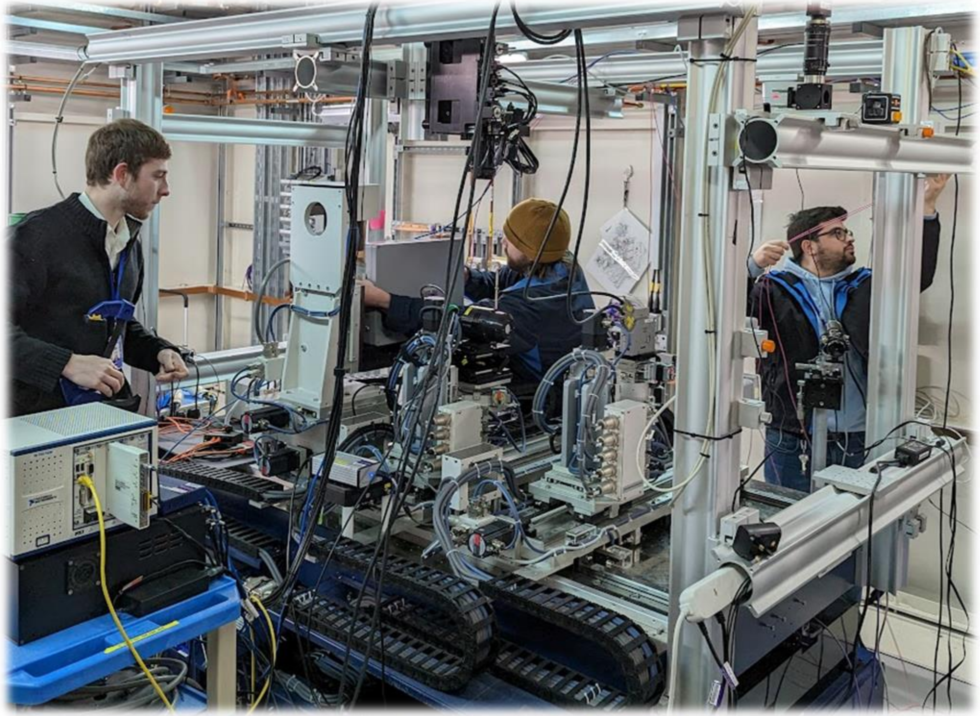
- Novel HF-CZT HEXITEC-MHz detector variants
  - New low-temp hybridisation (<80 °C) method
  - Redlen sensors with new Ti-anode technology

The $\text{HEXITEC}_{\text{MHz}}$ camera system

Summary

- Results revealed an ‘**excess leakage current**’ effect in **HF-CZT**
    - Not present in p-type Si results
- Arrhenius analysis suggests related to an **Indium-based CZT defect**
- Magnitude **dependent on incident X-ray flux**
    - Significant $>10^{5}$ ph s^{-1} mm^{-2}
    - **3.6 nA mm^{-2}** at **7×10^{7} ph s^{-1} mm^{-2}**
- At spectroscopic fluxes, lower excess currents measured.
    - **0.48 nA mm^{-2}** at **3×10^{5} ph s^{-1} mm^{-2}**
    - In-FPGA $HEXITEC_{MHz}$ firmware enables **real-time corrections**
- Further characterisation planned with $HEXITEC_{MHz}$
    - Validates detector’s capability for MHz materials characterisation

Please contact me with further questions: ben.cline@stfc.ac.uk



Team members at DLS B16 Test Beamline

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HEXITEC$_{MHz}$

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

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