Characterization and comparison of GaAs:Cr sensors coupled to Timepix family chips

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- **Some GaAs:Cr history in ESRF**

Num	Name	Chip	Thickness (µm)	Crystal growth	Manufacturer	Year	Results published
#1	TSU-V1	Timepix	516	V1	TSU	2016	Jinst, 2017(1)
#2	TSU-V2.1	Timepix	700	V2	TSU	2018	Jinst, 2020(2)
#3	TSU-V2.2	Timepix3	999	V2	TSU	2018	
#4	TSU-V3.1	Timepix3	500	V3	TSU	2021	
#5	TSU-V3.2	Timepix3	500	V3	TSU	2021	
#6	ADV-V1	Timepix3	500	V1	ADV	2023	

TSU: Tomsk State University, Russia
ADV: Advacam/Adavafab, Finland

(1) https://doi.org/10.1088/1748-0221/12/12/C12023
(2) https://doi.org/10.1088/1748-0221/16/01/p01032

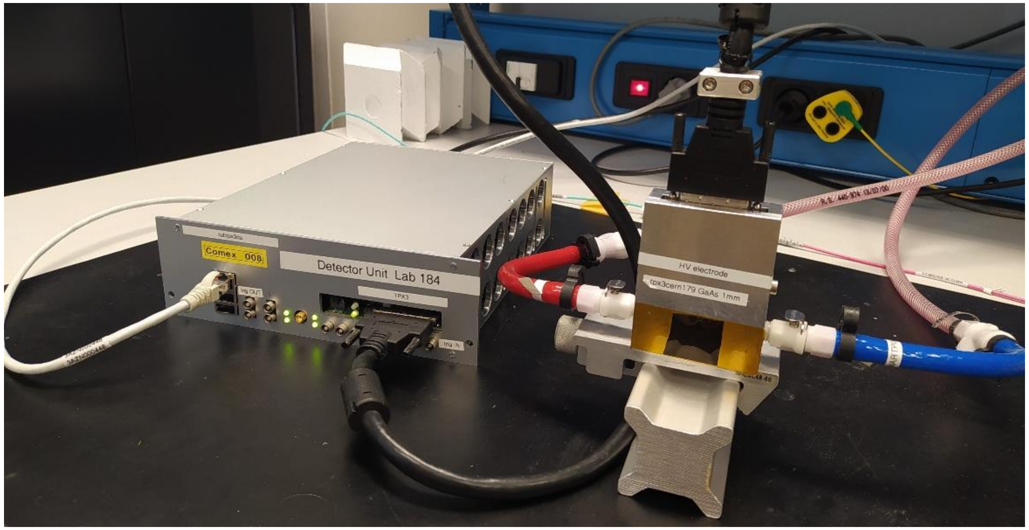
- **Goal: Provide an overview and compare of characterization results obtained with successive versions of GaAs:Cr**

CONTEXT

- **Readout systems used at the ESRF**
  - Timepix: MAXIPIX

	Timepix
Tech. node (nm)	250
Year	2005
Pixel size (μm)	55
# pixels (x x y)	256 x 256
Time bin (resolution)	10ns
Readout architecture	Frame based (sequential R/W)
Number of sides for tiling	3

  - Timepix3:



	Timepix3
Tech. node (nm)	130
Year	2014
Pixel size (μm)	55
# pixels (x x y)	256 x 256
Time bin (resolution)	1.6ns
Readout architecture	Data driven or Frame based (sequential R/W)
Number of sides for tiling	3

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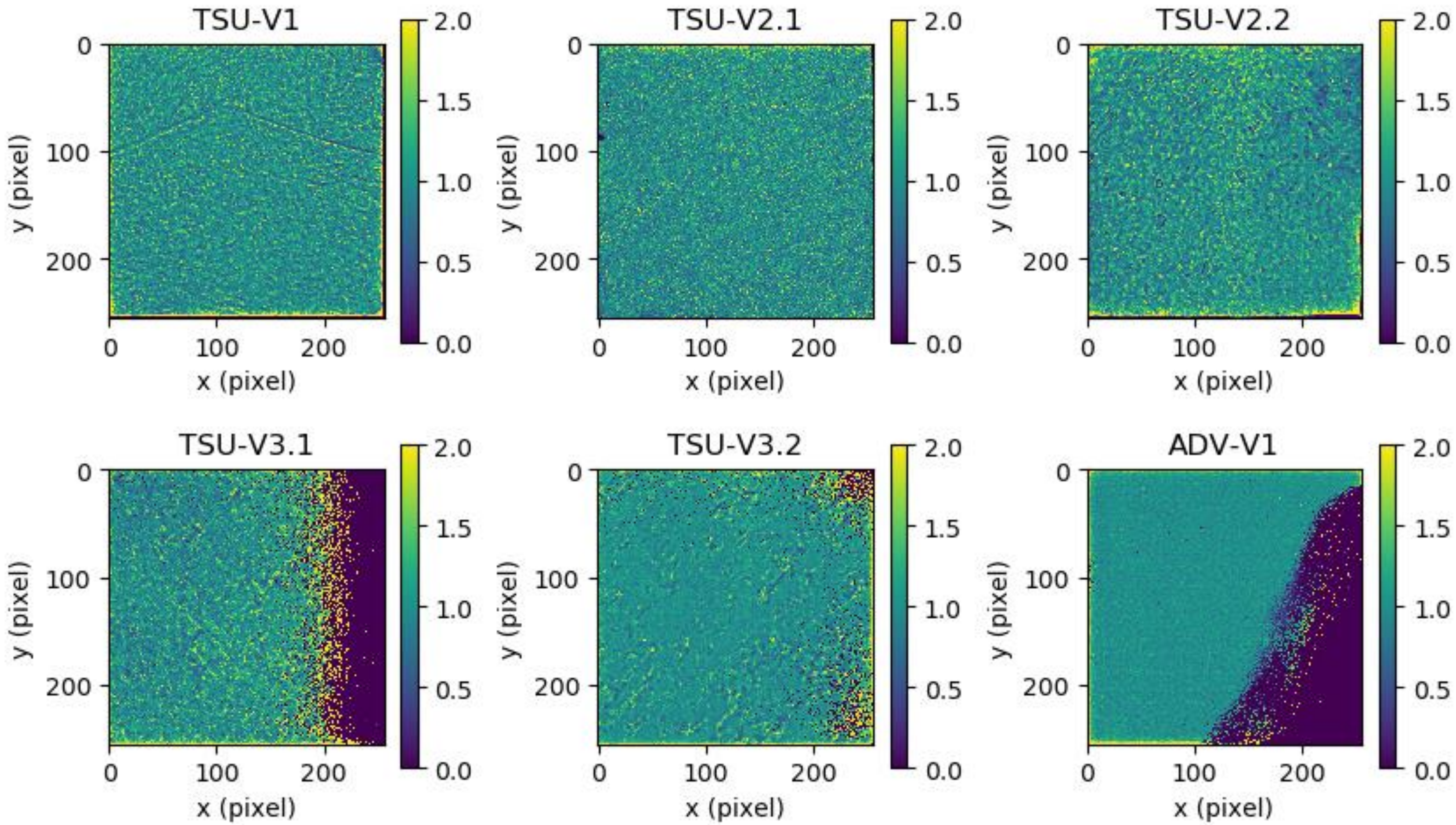
FLOOD IMAGES AND FLAT FIELD CORRECTION

- **Setup**
  - Source: laboratory X-ray source

Anode	Tube voltage	Tube current	Filter material	Filter thickness	Characteristic energy
Mo	25 kV_p	25 mA	Zr	100 µm	17 keV

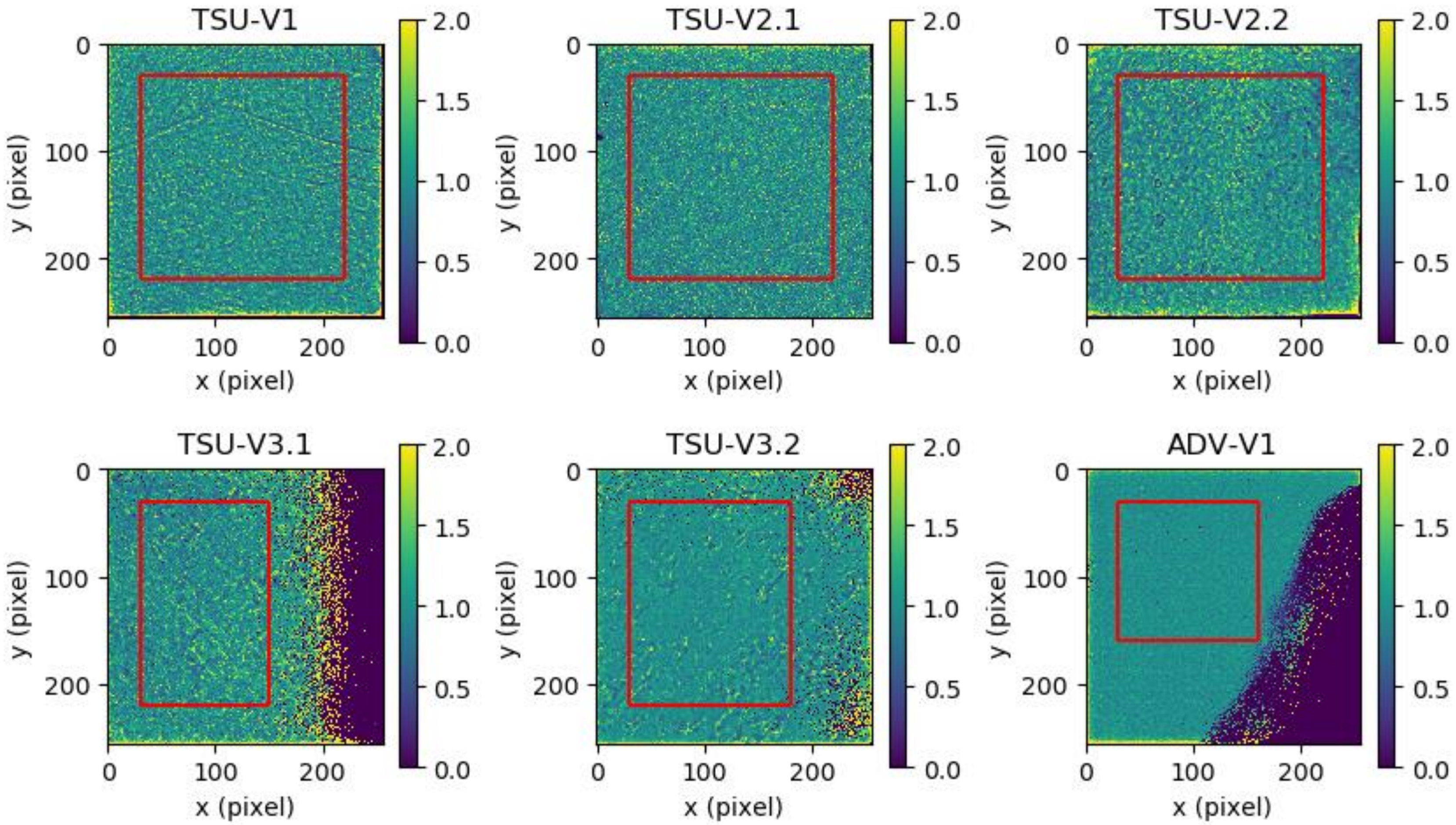
  - Flux: 2×10^6 $ph.mm^{-2}.s^{-1}$
  - Working distance: 1m
  - Energy threshold: 9keV

FLOOD IMAGES AFTER CALIBRATION



⇒ Bonding and breakage issues with the most recent detectors

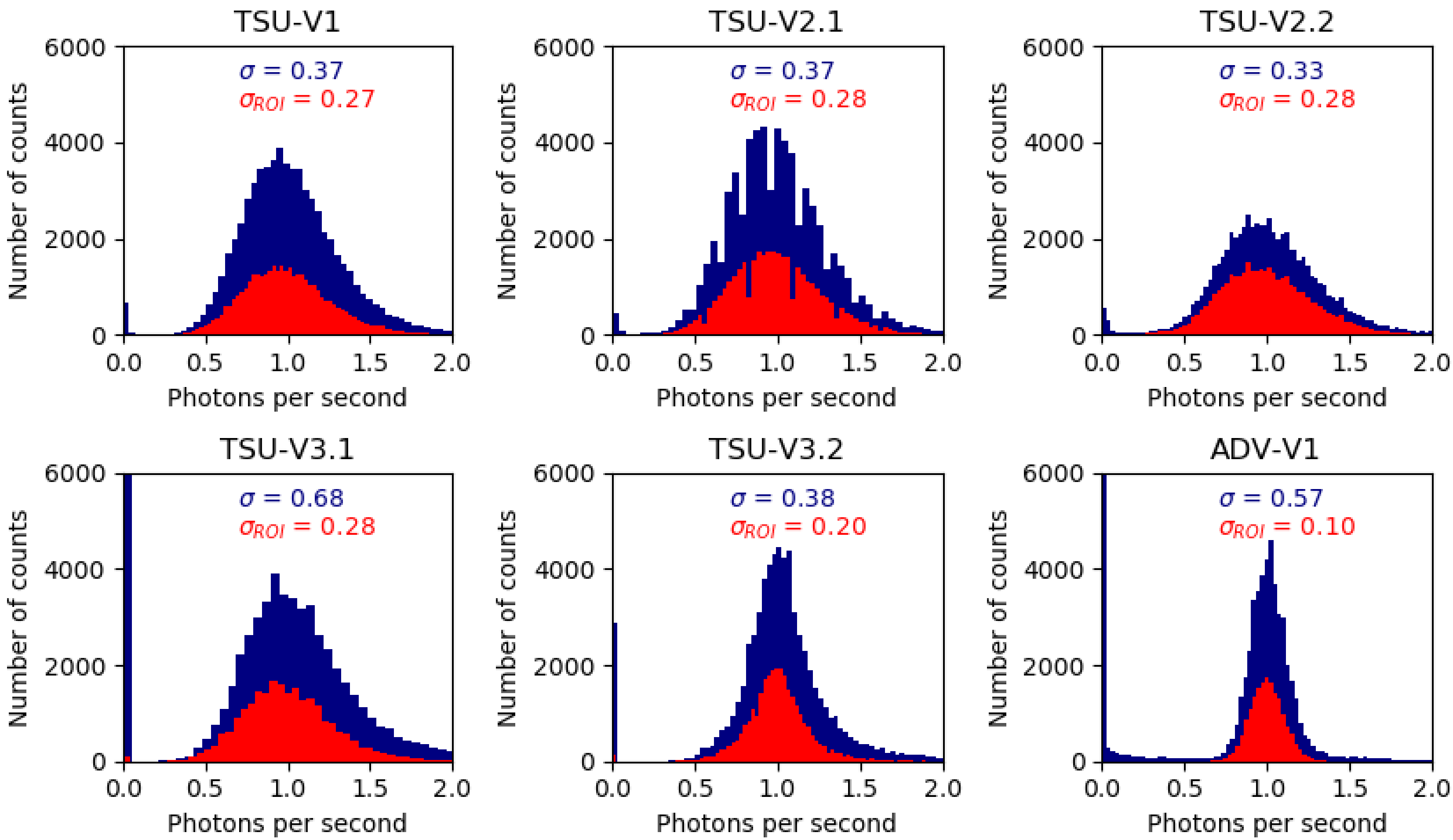
FLOOD IMAGES AFTER CALIBRATION



⇒ Bonding and breakage issues with the most recent detectors

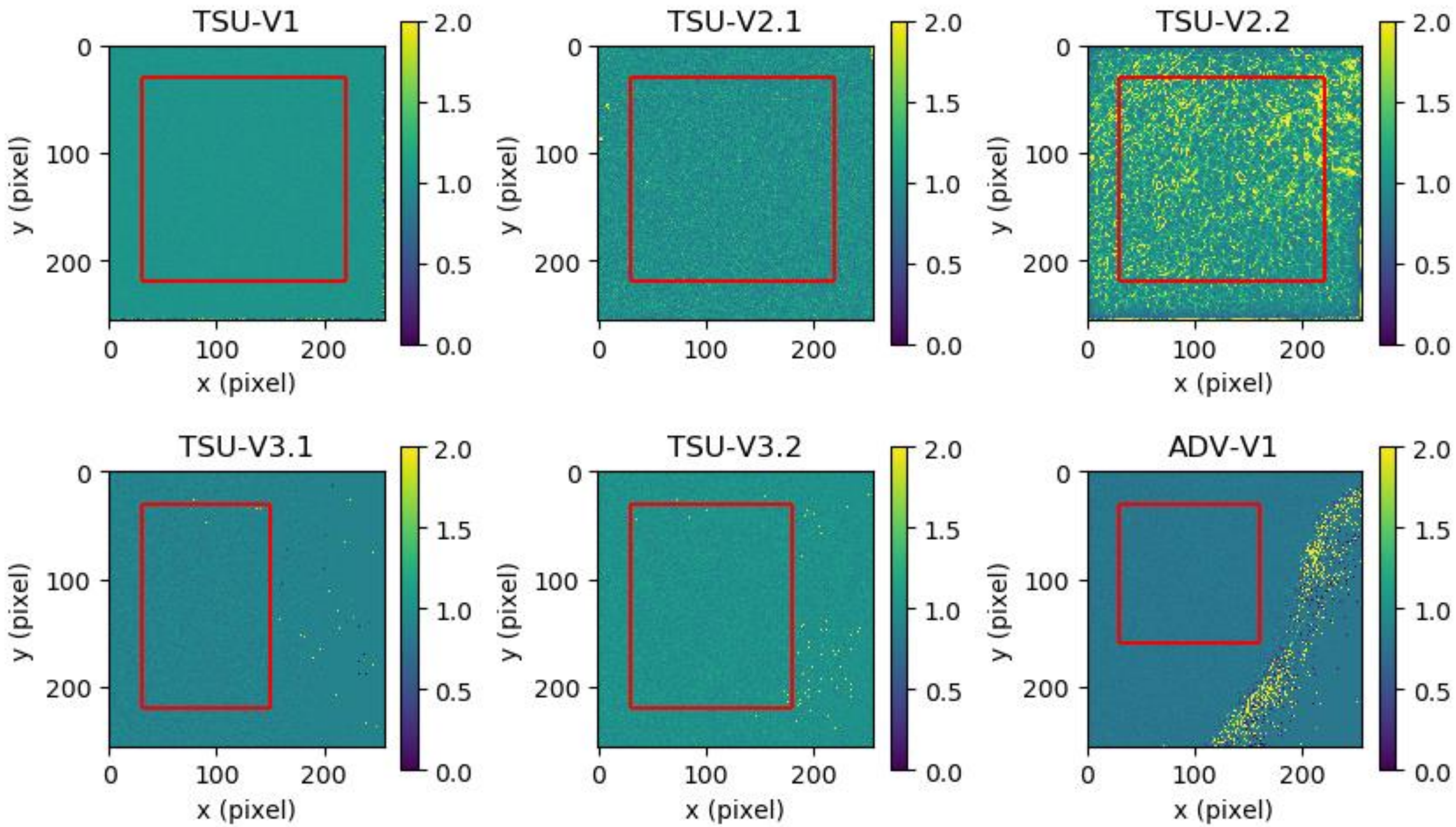
⇒ Characterizations on the ROI in red

FLOOD IMAGES AFTER CALIBRATION



⇒ The most homogenous sensors are ADV-V1 and TSU-V3.2 (ROI measurements)

FLAT FIELD (FF) CORRECTION

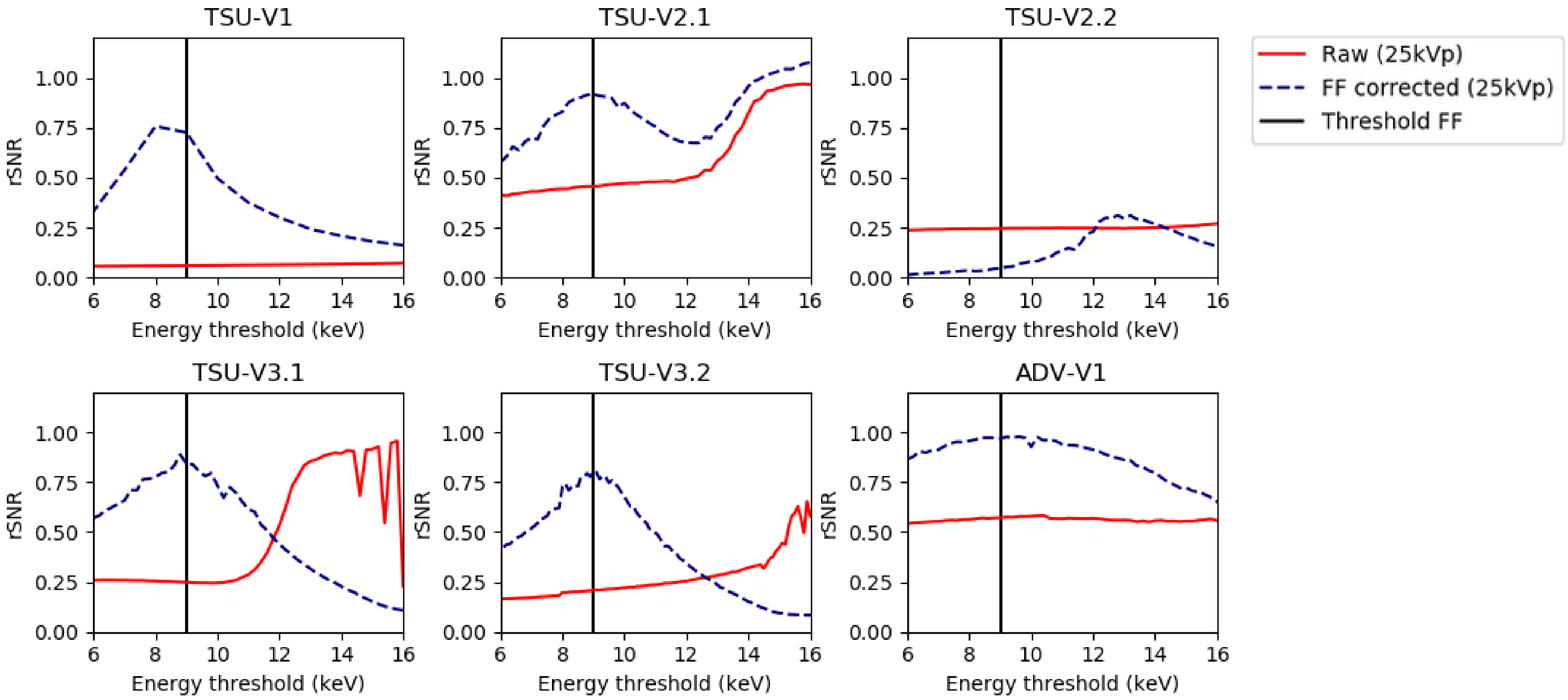


⇒ There is an obvious issue with the flat field correction of TSU-V2.2

FLAT FIELD (FF) CORRECTION EFFECTIVENESS

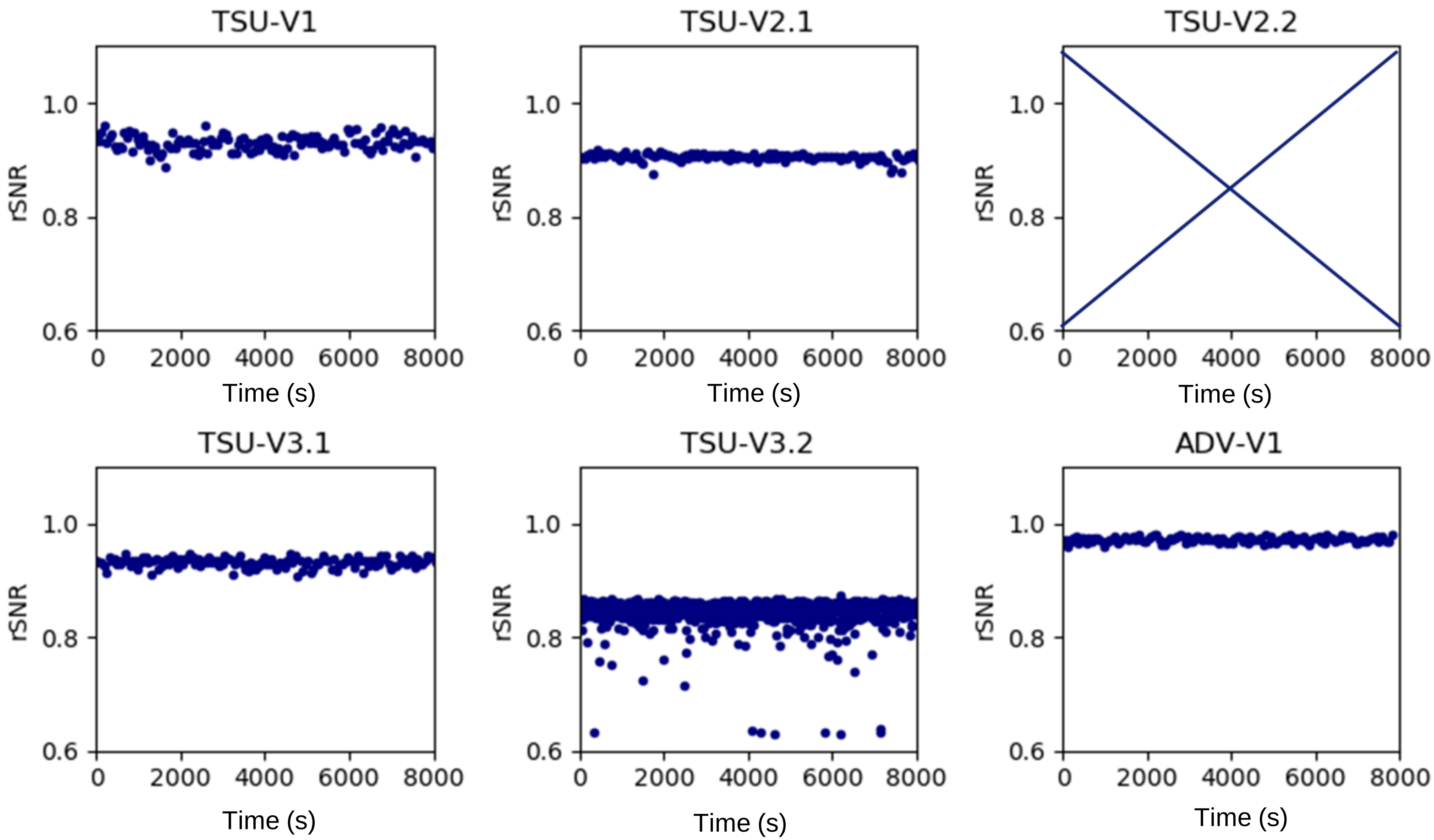
- **Relative Signal-to-Noise Ratio (rSNR)**

$$rSNR(ROI) = \frac{SNR_{image}(ROI)}{SNR_{poisson}(ROI)} = \frac{\sqrt{mean(ROI)}}{\sigma(ROI)}$$



⇒ The FF correction effectively improves the rSNR for all detectors (except TSU-V2.2)

- **Relative Signal-to-Noise Ratio (rSNR)**



⇒ Most effective and stable FF correction achieved for ADV-V1 followed by TSU-V2.1 and TSU-V3.1

FLOOD IMAGES AND FLAT FIELD CORRECTION

- **Takeaway messages for flood images and flat field correction**
  - The best sensor that we have to date in terms of homogeneity, FF correction efficiency and stability is the sensor from Advacam. BUT, to date we have only characterized one sensor so this still needs to be confirmed.
  - The experience that we have with TSU sensors is that for the same version the detectors the homogeneity and FF correction quality are not necessarily reproducible.

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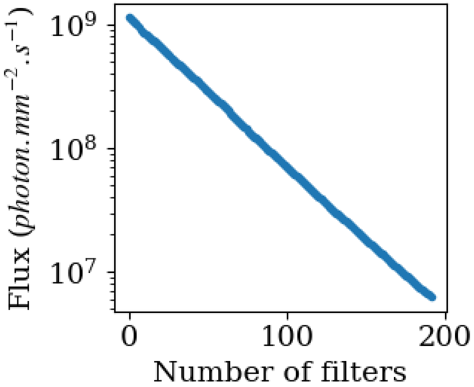
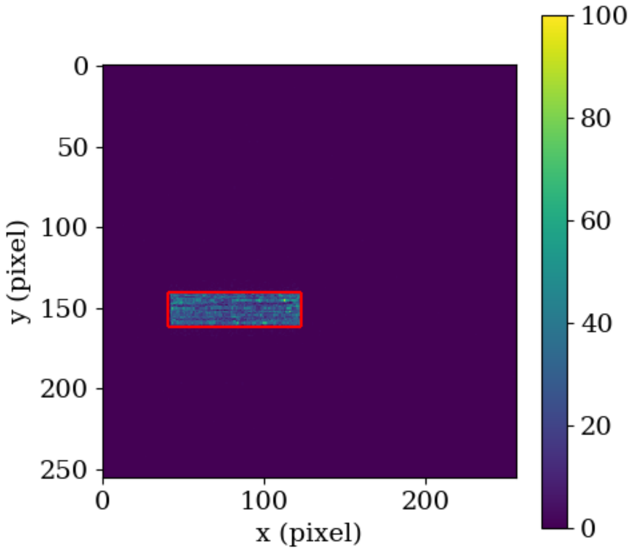
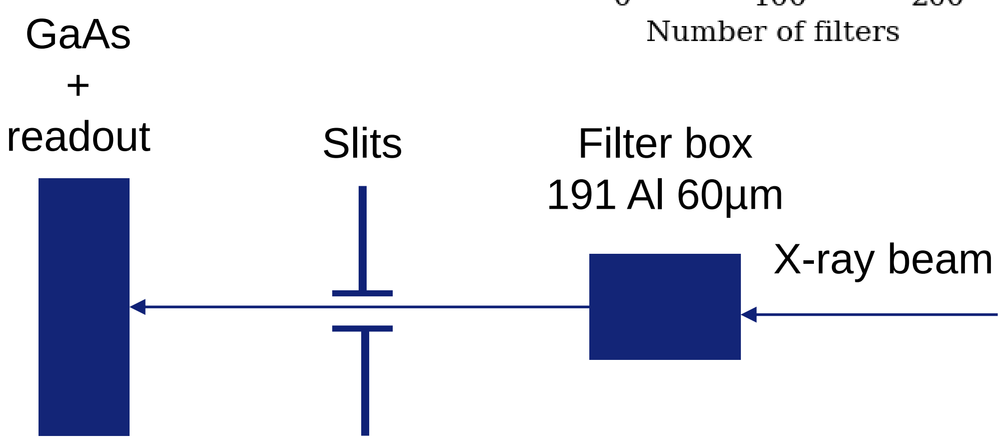
LINEARITY WITH INCIDENT FLUX

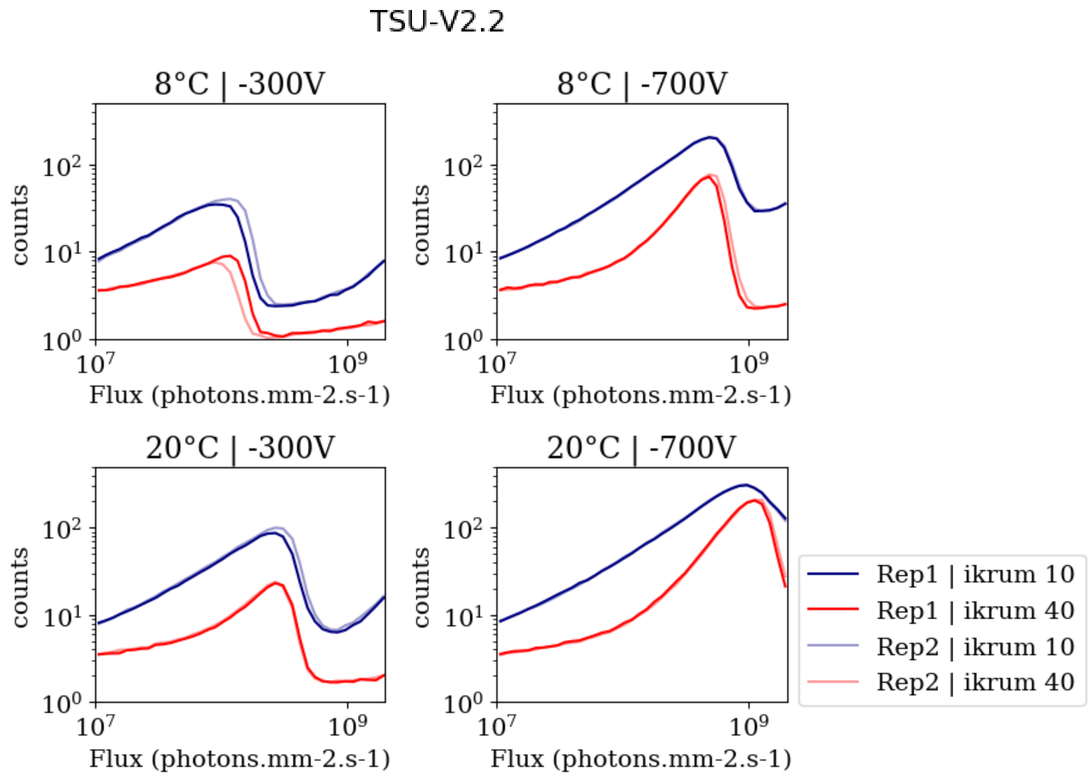
- **Setup for linearity limit measurement**
  - Source: 30keV monochromatic synchrotron beam provided by the BM05 beamline of the ESRF (7/8+1 mode)
  - Detector tested: TSU-V1, TSU-V2.2 and TSU-V3.2
  - Flux range: 2×10^7 - 2×10^9 $ph.mm^{-2}.s^{-1}$
  - Parameters tested
    - Temperature: 8°C and 20°C
    - Bias: -300V and -700V
    - Ikrum: 10 and 40







- **Linearity limit measurement**
  - Split plot experimental design[1] with 2 replicates
    - None randomized factors: Detector and Temperature
    - Randomized factors: Bias and ikrum
  - The linearity limit is defined as highest photon flux for which the number of counts stays linear.



(1) D. C. Montgomery, *Design and analysis of experiments*, Eighth edition. Hoboken, NJ: John Wiley & Sons, Inc, 2013.

- **Linearity limit measurement**
  - Split plot experimental design[1] with 2 replicates
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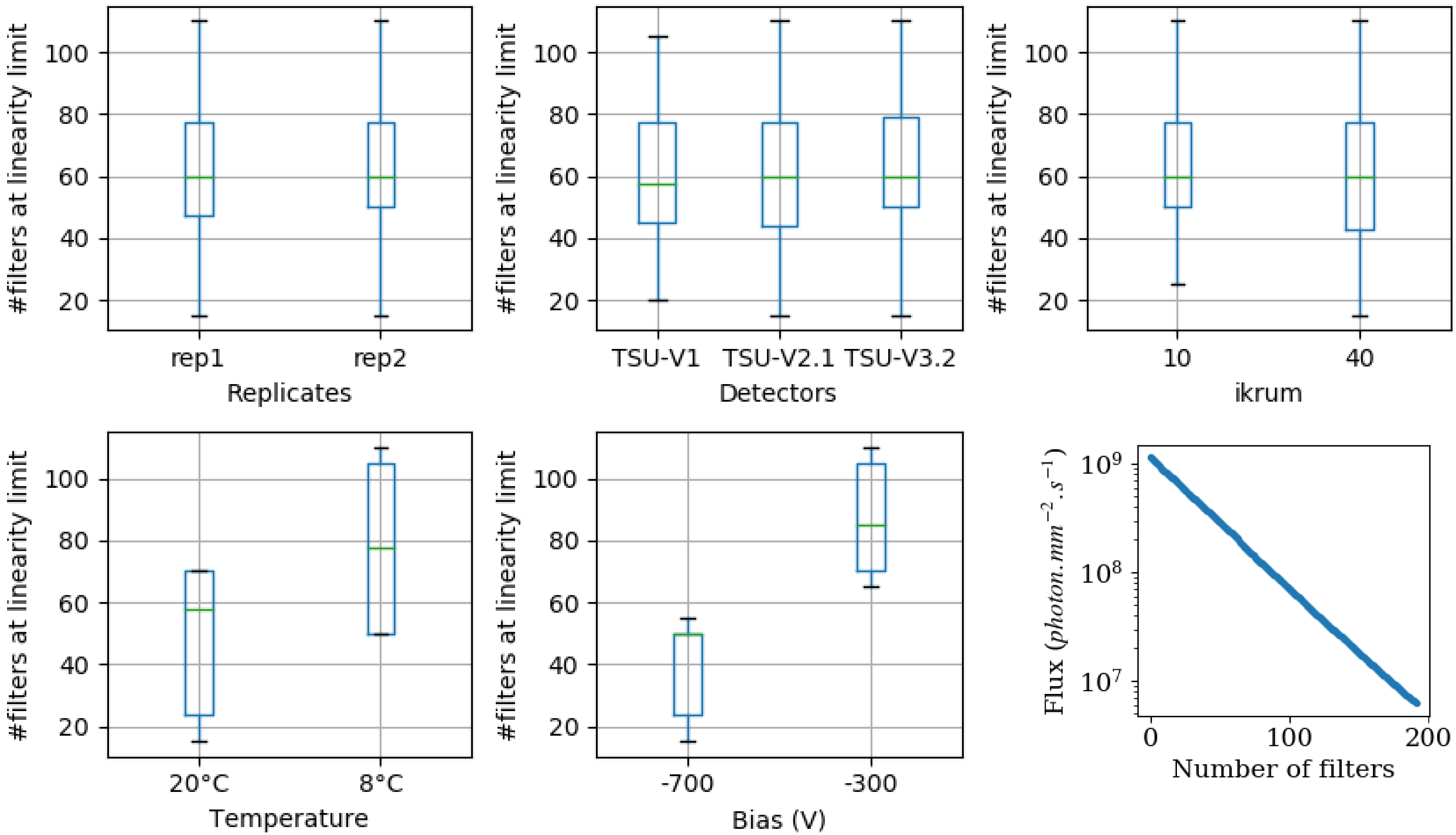
	replicates	rep1						rep2					
	detector	TSU-V3.2		TSU-V2.1		TSU-V1		TSU-V3.2		TSU-V2.1		TSU-V1	
	temperature	8°C	20°C	8°C	20°C	8°C	20°C	8°C	20°C	8°C	20°C	8°C	20°C
ikrum	bias												
10	-300	105.0	65.0	110.0	70.0	100.0	70.0	110.0	65.0	100.0	70.0	100.0	65.0
	-700	55.0	40.0	50.0	25.0	50.0	30.0	55.0	50.0	50.0	25.0	50.0	30.0
40	-300	110.0	70.0	100.0	70.0	105.0	65.0	105.0	70.0	110.0	70.0	105.0	65.0
	-700	55.0	15.0	50.0	20.0	50.0	20.0	50.0	15.0	50.0	15.0	50.0	20.0

(1) D. C. Montgomery, *Design and analysis of experiments*, Eighth edition. Hoboken, NJ: John Wiley & Sons, Inc, 2013.

LINEARITY WITH INCIDENT FLUX



⇒ The linearity limit increases with both the temperature and the bias.

⇒ The linearity limit appears to be linked to the polarization effect which is mitigated at higher temperature and bias.

LINEARITY WITH INCIDENT FLUX

- **Takeaway messages for linearity limit of GaAs:Cr (ohmic)**
  - The higher the temperature, the higher the linearity limit.
  - The higher the bias, the higher the linearity limit.
  - Highest linearity limit recorded: 1×10^{9} $ph.mm^{-2}.s^{-1}$ (20°C, -1.4kV/mm) before sensor breakdown

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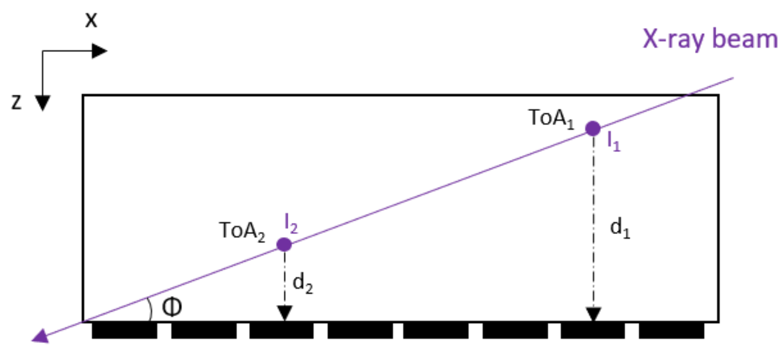
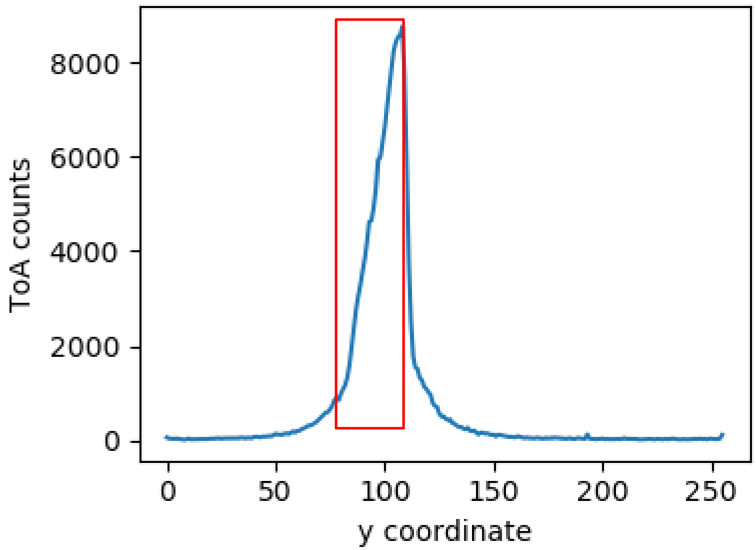
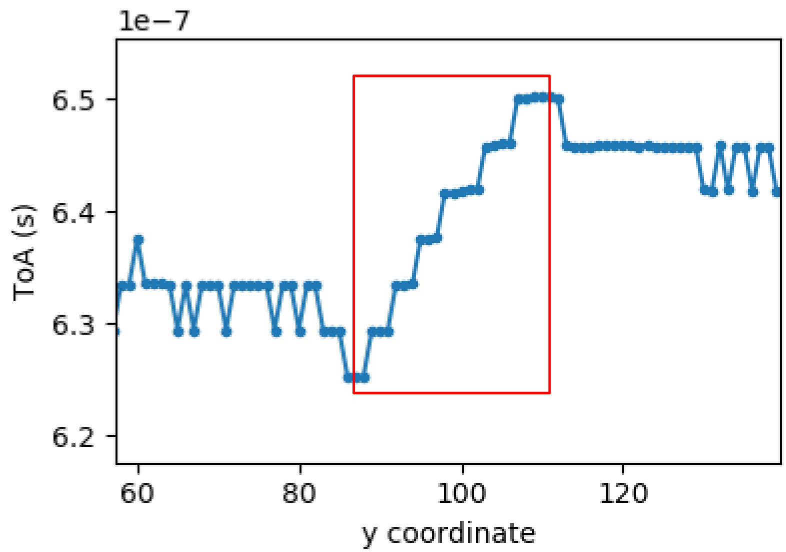
- **Setup grazing incidence measurements: electron drift velocity estimation**
  - Source: 50keV monochromatic synchrotron beam provided by the BM05 beamline of the ESRF (4-bunch mode)
  - Detectors tested: TSU-V2.2, TSU-V3.1, TSU-V3.2, ADV-V1 (only TPX3)
  - Parameters tested:
    - Temperature: 12°C, 24°C, 36°C
    - Electric field: -60V/mm to -160V/mm (20V/mm step)
  - Beam is focused on 1 pixel by compact transfocator (Al refractive lenses)
  - Sensor is tilted by an angle Φ=19° with respect to the beam
  - We measure the Time of Arrival for the line of pixels irradiated

$$v_{drift} = \frac{d_1 - d_2}{ToA_1 - ToA_2} = \frac{distance}{t_{transit}}$$

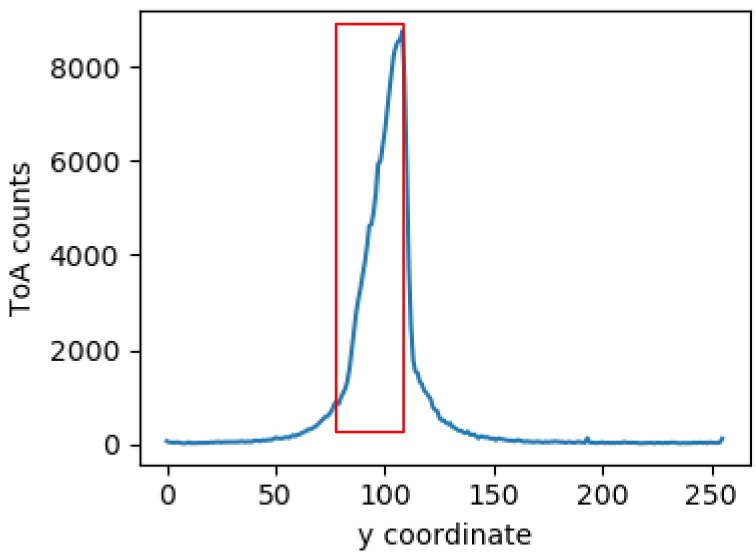


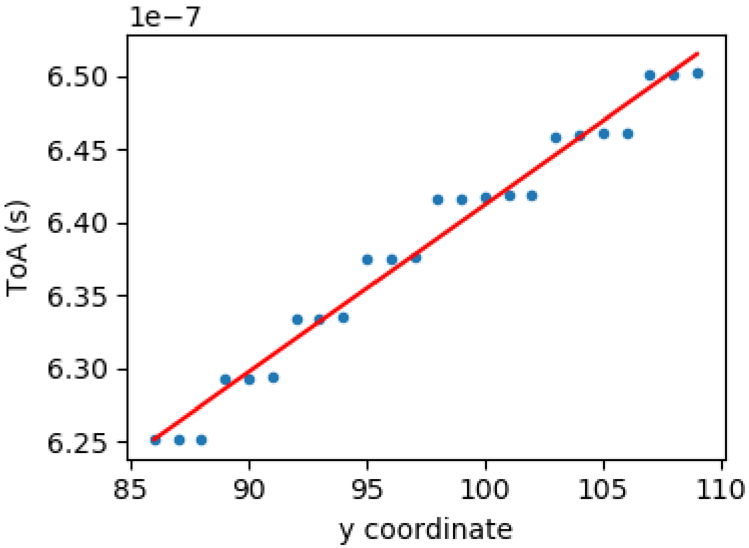
- **Measurement procedure for electron drift velocity**
  - ToA measurement is synchronous with the bunches
  - The ROI is defined by looking at the ToA counts as a function of the y coordinate (equivalent to depth in the sensor)





- **Measurement procedure for electron drift velocity**
  - ToA measurement is synchronous with the bunches
  - The ROI is defined by looking at the ToA counts as a function of the y coordinate (equivalent to depth in the sensor)
  - Linear regression of ToA VS y coordinate in the ROI to get the drift velocity





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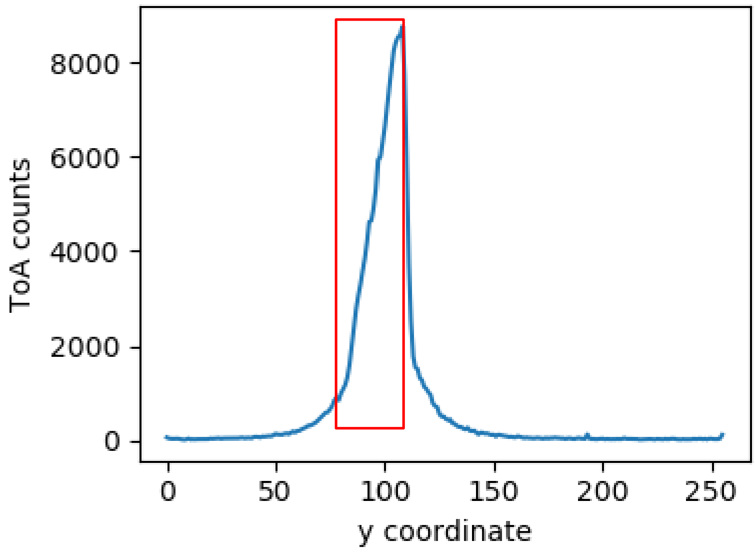

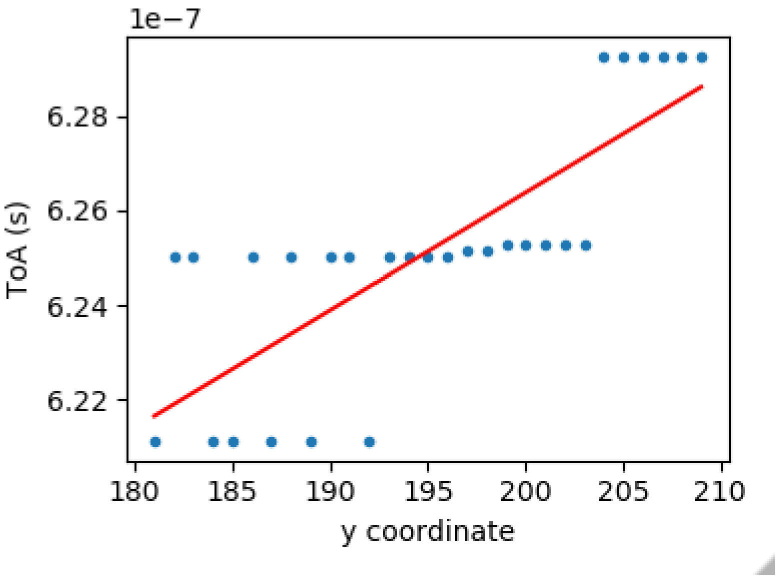

  - For some sets of parameters the drift velocity cannot be extracted

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CHARGE TRANSPORT PROPERTIES

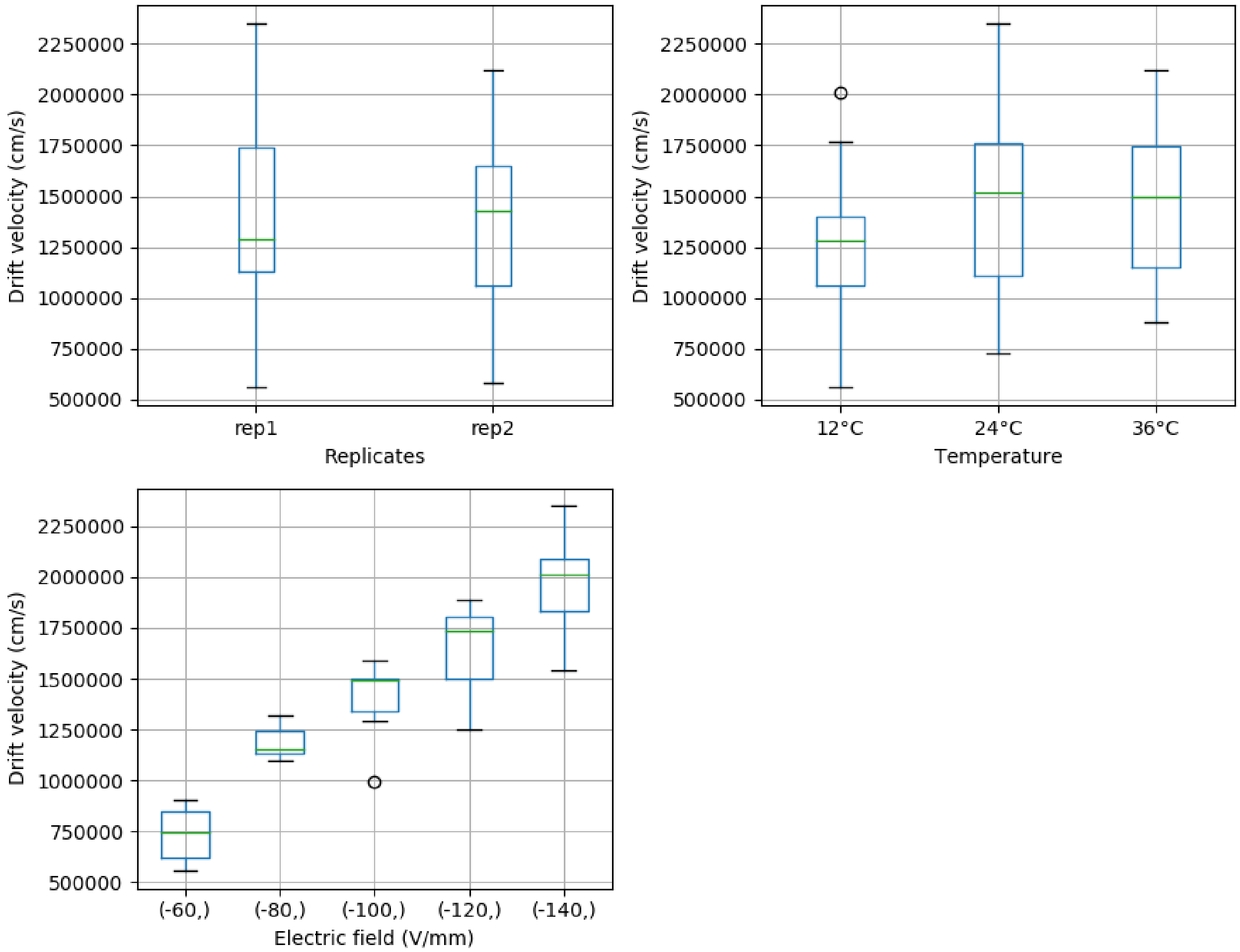
- ## Electron drift velocity

replicates	detector	electric field (V/mm) / temperature	-60	-80	-100	-120	-140	-160
rep1	ADV-V1	12°C	559000.0	1270000.0	1290000.0	1250000.0	1770000.0	3000000.0
		24°C	725000.0	1100000.0	1590000.0	1820000.0	2350000.0	3380000.0
		36°C	878000.0	1160000.0	1500000.0	1710000.0	2010000.0	2980000.0
	TSU-V3.2	12°C	NaN	529000.0	718000.0	853000.0	1460000.0	2070000.0
		24°C	1450000.0	1530000.0	1510000.0	2890000.0	NaN	NaN
		36°C	1210000.0	1390000.0	2360000.0	3600000.0	4680000.0	NaN
	TSU-V3.1	12°C	713000.0	643000.0	679000.0	914000.0	932000.0	1140000.0
		24°C	1170000.0	1450000.0	1390000.0	1310000.0	1980000.0	2970000.0
		36°C	1490000.0	1820000.0	1430000.0	2120000.0	3000000.0	NaN
	TSU-V2.2	12°C	NaN	390000.0	812000.0	732000.0	1110000.0	2160000.0
		24°C	NaN	375000.0	969000.0	1060000.0	1040000.0	3360000.0
		36°C	NaN	NaN	304000.0	255000.0	542000.0	1880000.0
rep2	ADV-V1	12°C	581000.0	1320000.0	993000.0	1430000.0	2010000.0	2520000.0
		24°C	771000.0	1130000.0	1500000.0	1890000.0	1540000.0	1540000.0
		36°C	902000.0	1150000.0	1490000.0	1760000.0	2120000.0	2630000.0
	TSU-V3.2	12°C	1120000.0	862000.0	974000.0	1350000.0	1740000.0	2050000.0
		24°C	NaN	1590000.0	1810000.0	NaN	NaN	NaN
		36°C	1230000.0	1430000.0	2450000.0	3760000.0	4800000.0	NaN
	TSU-V3.1	12°C	613000.0	634000.0	660000.0	702000.0	1470000.0	1380000.0
		24°C	983000.0	1420000.0	1380000.0	1860000.0	2260000.0	NaN
		36°C	1390000.0	1940000.0	NaN	1940000.0	2800000.0	3960000.0
	TSU-V2.2	12°C	NaN	629000.0	835000.0	1070000.0	908000.0	1580000.0
		24°C	NaN	460000.0	963000.0	1750000.0	2340000.0	2880000.0
		36°C	NaN	2320000.0	835000.0	2400000.0	NaN	5120000.0

- **Electron drift velocity**

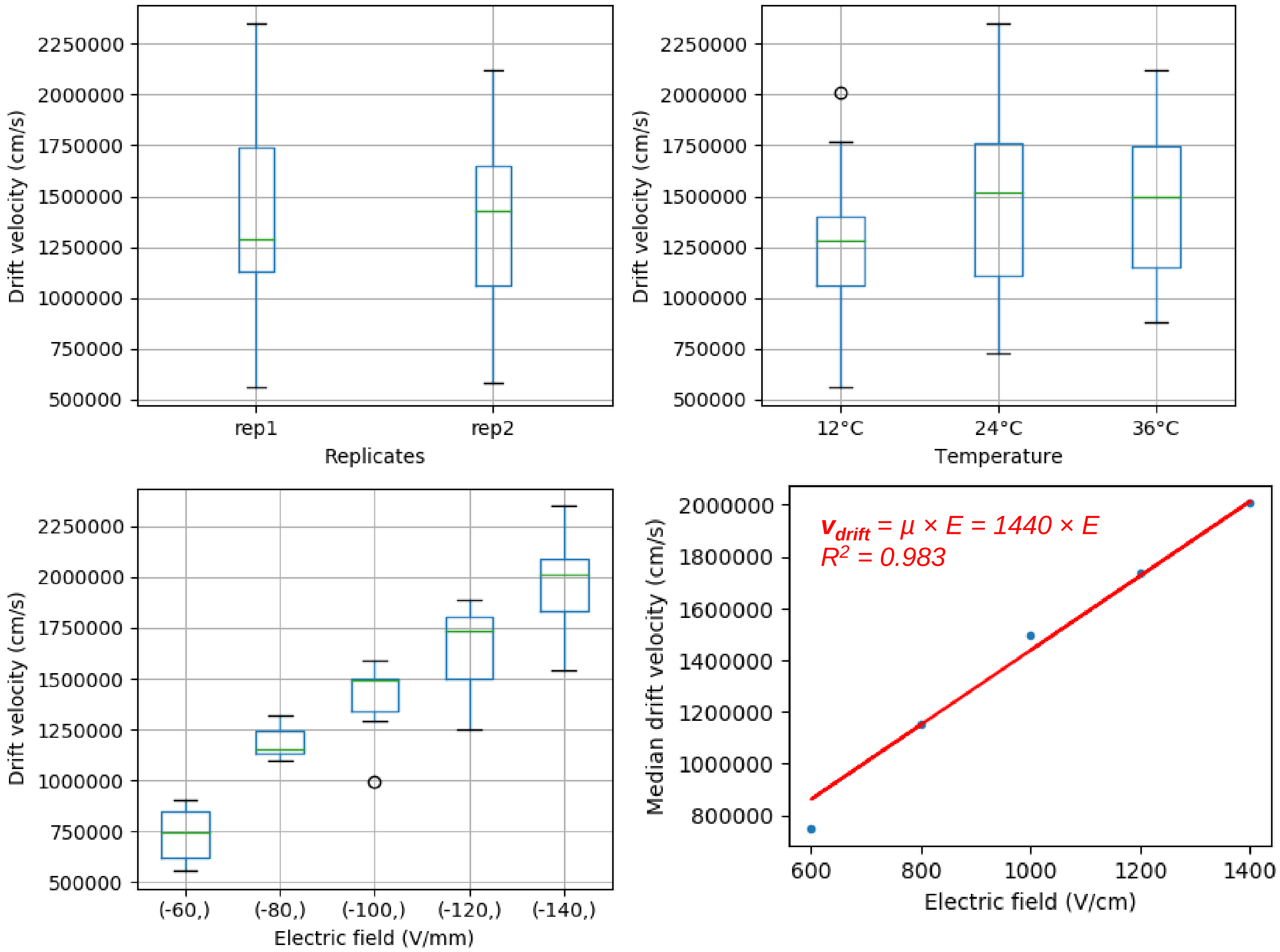
replicates	detector	electric field (V/mm) / temperature	-60	-80	-100	-120	-140	-160
rep1	ADV-V1	12°C	559000.0	1270000.0	1290000.0	1250000.0	1770000.0	3000000.0
		24°C	725000.0	1100000.0	1590000.0	1820000.0	2350000.0	3380000.0
		36°C	878000.0	1160000.0	1500000.0	1710000.0	2010000.0	2980000.0
	TSU-V3.2	12°C	NaN	529000.0	718000.0	853000.0	1460000.0	2070000.0
		24°C	1450000.0	1530000.0	1510000.0	2890000.0	NaN	NaN
		36°C	1210000.0	1390000.0	2360000.0	3600000.0	4680000.0	NaN
	TSU-V3.1	12°C	713000.0	643000.0	679000.0	914000.0	932000.0	1140000.0
		24°C	1170000.0	1450000.0	1390000.0	1310000.0	1980000.0	2970000.0
		36°C	1490000.0	1820000.0	1430000.0	2120000.0	3000000.0	NaN
	TSU-V2.2	12°C	NaN	390000.0	812000.0	732000.0	1110000.0	2160000.0
		24°C	NaN	375000.0	969000.0	1060000.0	1040000.0	3360000.0
		36°C	NaN	NaN	304000.0	255000.0	542000.0	1880000.0
rep2	ADV-V1	12°C	581000.0	1320000.0	993000.0	1430000.0	2010000.0	2520000.0
		24°C	771000.0	1130000.0	1500000.0	1890000.0	1540000.0	1540000.0
		36°C	902000.0	1150000.0	1490000.0	1760000.0	2120000.0	2630000.0
	TSU-V3.2	12°C	1120000.0	862000.0	974000.0	1350000.0	1740000.0	2050000.0
		24°C	NaN	1590000.0	1810000.0	NaN	NaN	NaN
		36°C	1230000.0	1430000.0	2450000.0	3760000.0	4800000.0	NaN
	TSU-V3.1	12°C	613000.0	634000.0	660000.0	702000.0	1470000.0	1380000.0
		24°C	983000.0	1420000.0	1380000.0	1860000.0	2260000.0	NaN
		36°C	1390000.0	1940000.0	NaN	1940000.0	2800000.0	3960000.0
	TSU-V2.2	12°C	NaN	629000.0	835000.0	1070000.0	908000.0	1580000.0
		24°C	NaN	460000.0	963000.0	1750000.0	2340000.0	2880000.0
		36°C	NaN	2320000.0	835000.0	2400000.0	NaN	5120000.0

- **Electron drift velocity: example of ADV-V1**



⇒ The drifts velocity depends only on electric field (saturation not reached)

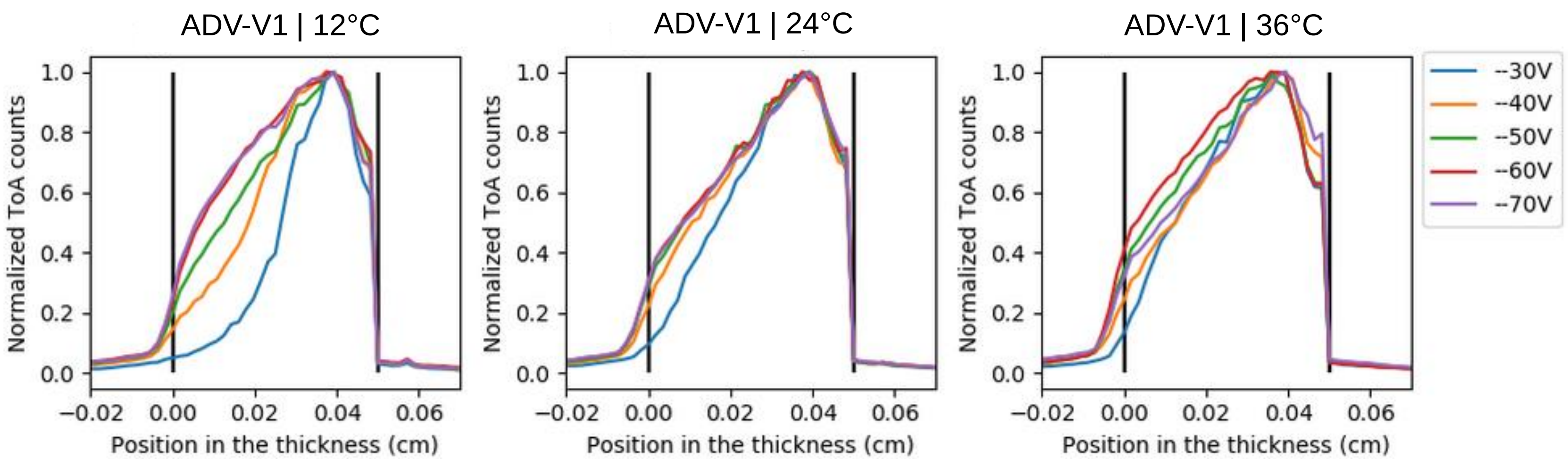
- **Electron drift velocity: example of ADV-V1**



⇒ The drifts velocity depends only on electric field (saturation not reached)

⇒ Assuming constant electric field, the mobility is estimated to be 1440 $cm^2.V^{-1}.s^{-1}$

- **A few words about electric field distribution and electron mobility**
  - ToA count decorrelated from X-ray absorption VS depth would be constant in a sensor with constant electric field
  - Here it is obvious that the electric field distribution is not constant in the sensor so mobility estimation are to be taken with a grain of salt



- **General results**
  - The linearity of the drift velocity with electric field is verified for all sensors (except for TSU-V3.2) and the saturation is not reached
  - The average electron mobility for all sensors is about 1500 $cm^2.V^{-1}.s^{-1}$

- **Takeaway messages on charge transport properties**
  - Measuring transit time is a tricky balance between absorption, grazing angle, bias and time resolution of the chip.
  - Mobility estimation is difficult because the electric field distribution is not constant through the depth of the sensors.
  - For all of the sensors measured electron mobility has on average 1500 $cm^2.V^{-1}.s^{-1}$

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CONCLUSION AND OUTLOOK

- **GaAs:Cr sensors tested**
  - 6 detectors
  - 4 generations
  - 5 sensors from TSU, 1 sensor from Advacam
- **Flood image and Flat field correction**
  - Experience with TSU: sensor quality not reproducible within the same generation
  - Advacam sensor is the best so far BUT only one was tested so no information on reproducibility yet
- **Linearity with incident X-ray flux at 30keV**
  - Linearity limit due to sensor (polarization effects)
  - Higher temperature and higher bias lead to higher linearity limit
- **Charge transport properties**
  - Electric field distribution not constant in the GaAs detectors
  - Electron mobility on average 1500 $cm^2.V^{-1}.s^{-1}$ for all detectors tested