X-ray imaging with high-Z sensors for the ESRF-EBS Upgrade

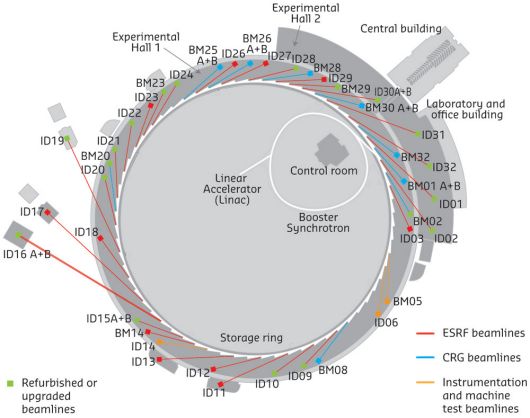
Stergios Tsigaridas

PIXEL2018, Taipei
December 13, 2018

The European Synchrotron | ESRF

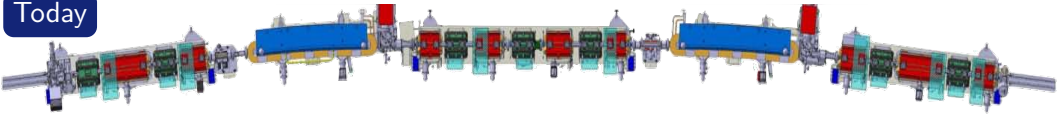
European Synchrotron Radiation Facility - ESRF

- ESRF is a 3rd generation synchrotron located in Grenoble/France
- 22 partner nations (13 Members states and 9 Scientific Associates)
- Offering 44 beamlines in total
- More than 5000 individual user visits per year

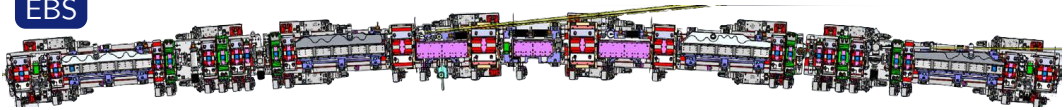


ESRF EBS Upgrade Programme

Today



EBS



- Use same tunnel - new storage ring
- Brilliance and coherence will be increased by a factor 100
- Upgrade programme for beam instrumentation and detectors

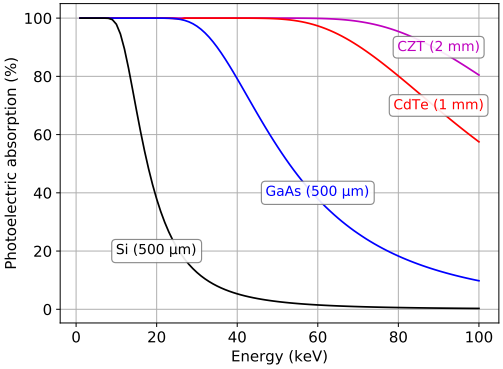
e^- beam properties	Today	EBS
Energy (GeV)	6.04	6
Multi-bunch current (mA)	200	200
Circumference (m)	844.39	843.98
Horizontal emittance (pm · mrad)	4000	140
Vertical emittance (pm · mrad)	4	5

Ref: ESRF Upgrade Phase II (Technical Design Study)

Hybrid pixel detector developement at ESRF

- Need for efficient detectors at moderate and high x-ray energies (30-100 keV)
- Research programme focusing on high-Z sensors for direct detection
- Photon counting or charge integrating

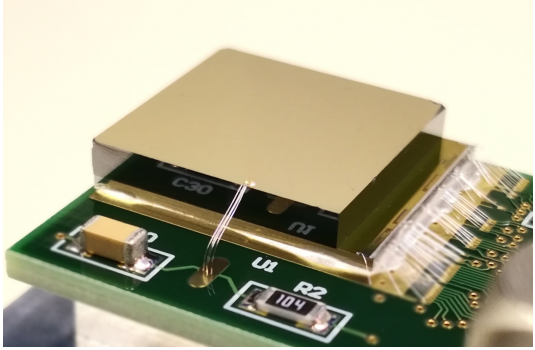
Property	Si	GaAs.	CdTe	CZT
Z (average)	14	32	50	49.1
Density ($g\,cm^{-3}$)	2.33	5.32	5.85	5.81
Energy gap (eV)	1.12	1.42	1.44	$\geqslant$1.6
Intr. carrier conc. (cm^{-3})	$\sim 10^{10}$	$2 \cdot 10^{6}$	$\sim 10^{7}$	$\sim 10^{7}$
W-value (eV)	3.62	4.3	4.43	4.64



Ref: Data obtained from XCOM NIST database

Hybrid pixel detectors for photon counting

- Medipix/Timepix family of chips
- 256 × 256 pixels, 55 μm pitch
- Total area of 2 cm^2

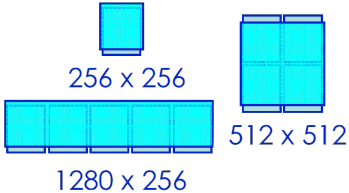


- Single or multi-chip modules
- Sensor is bump bonded to chip
- Wire bonds to chip carrier board

Table : Portfolio of high-Z sensors

Sensor	Thickn. (mm)	Pixel (μm)	Contact (type)	Vendor
CdTe	1	55	Ohmic	Acrorad
GaAs	0.5	55	Ohmic	Tomsk
CZT	2	55	Schottky	Redlen
CZT	2	110		
⋮	⋱		⋮	

Maxipix readout system



Ref: C. Ponchut et al. 2011 JINST 6 C01069

- Developed by ESRF (Medipix2/Timepix)
- 1.4 kHz maximum frame rate
- $2 \cdot 10^5$ counts/pixel maximum count rate
- 0.29 ms dead time at 100 MHz clock
- Minimum threshold $\sim$ 4 keV
- 11810 pixel counter depth

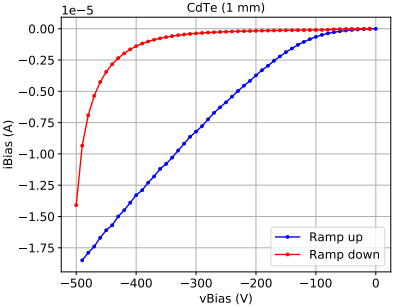
How to choose "the sensor" (?)

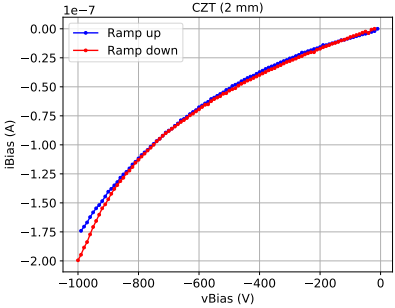
- Apply a common characterization procedure

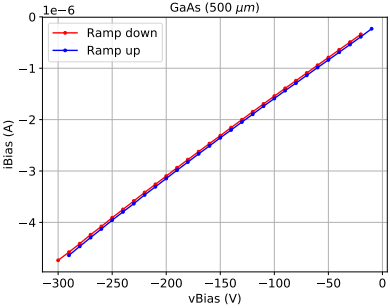
- Lab/X-ray generator
  - Wide filtered X-ray beam
  - Flat field images, count rate/stability tests
  - Imaging performance and spatial resolution
  - Charge collection efficiency tests

- Synchrotron beamline
  - Micro-focused (5-10 μm) monochromatic beam
  - Sub-micron precision translation stages
  - Spatial characteristics of the sensor (resolution, distortions)
  - Single pixel spectra

Leakage current vs bias voltage



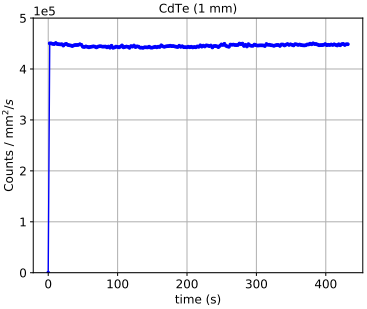


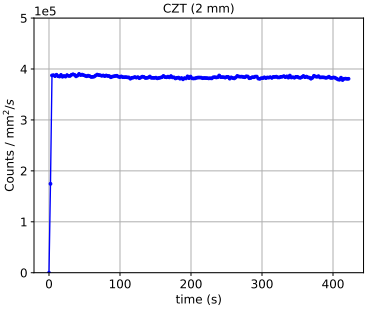


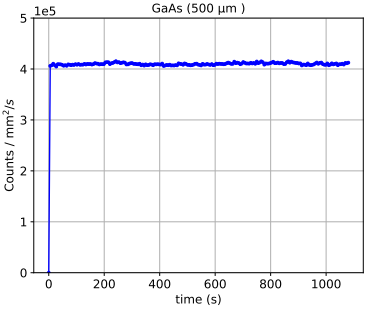
	CdTe	CZT	GaAs.
Sensor bias voltage (V)	-500	-1000	-300
Bias leakage current (μA)	20*	0.2	5
Equivalent pixel leakage current (pA)	305	3	76

Count rate tests

- Detector 1.5 m away from source
- Ramp up voltage and X-rays on
- Ag Anode/100 μm filter (∼ 22 keV)
- Generator settings (35 kV/25 mA)

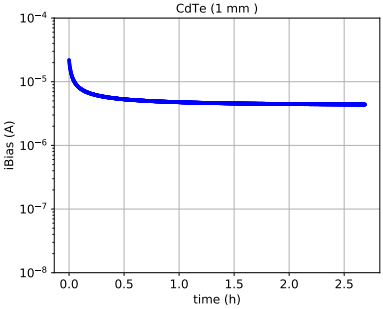


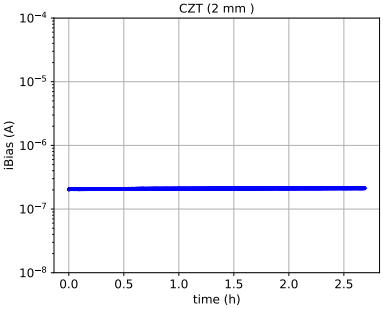


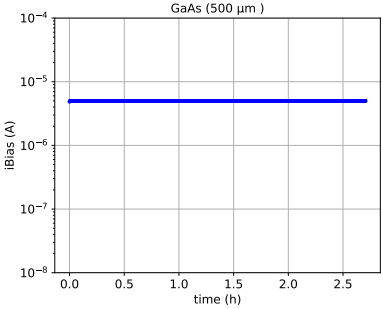


Leakage current stability

- Detector 1.5 m away from source
- Ramp up voltage and X-rays on
- Ag Anode/100 μm filter (∼ 22 keV)
- Generator settings (35 kV/25 mA)

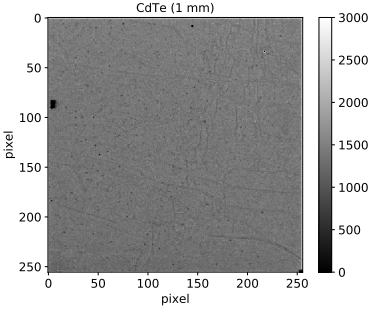


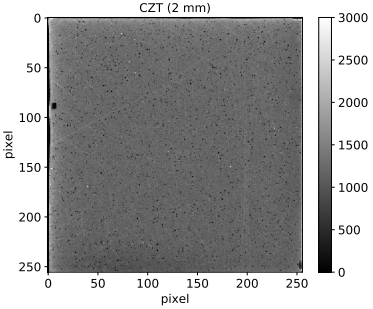


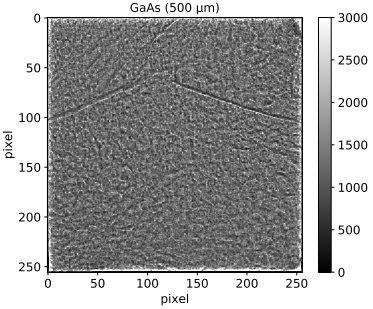


Flat field images (1 s exposure)

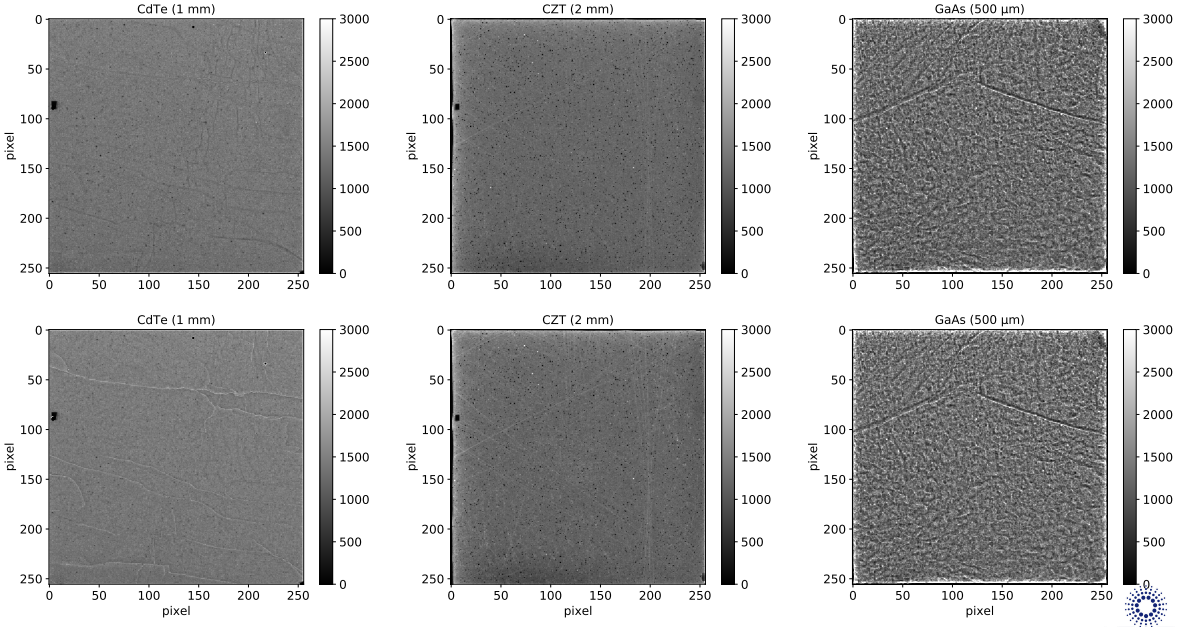
- Information about the quality of sensor/bump bonding/etc
- Tiny dots correspond to masked or unconnected pixels
- Defects appear with the form of lines or blobs
- How does this affect the performance??



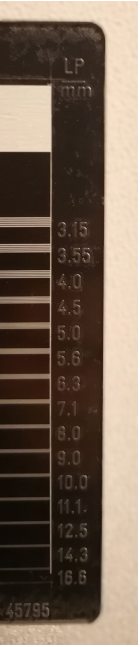


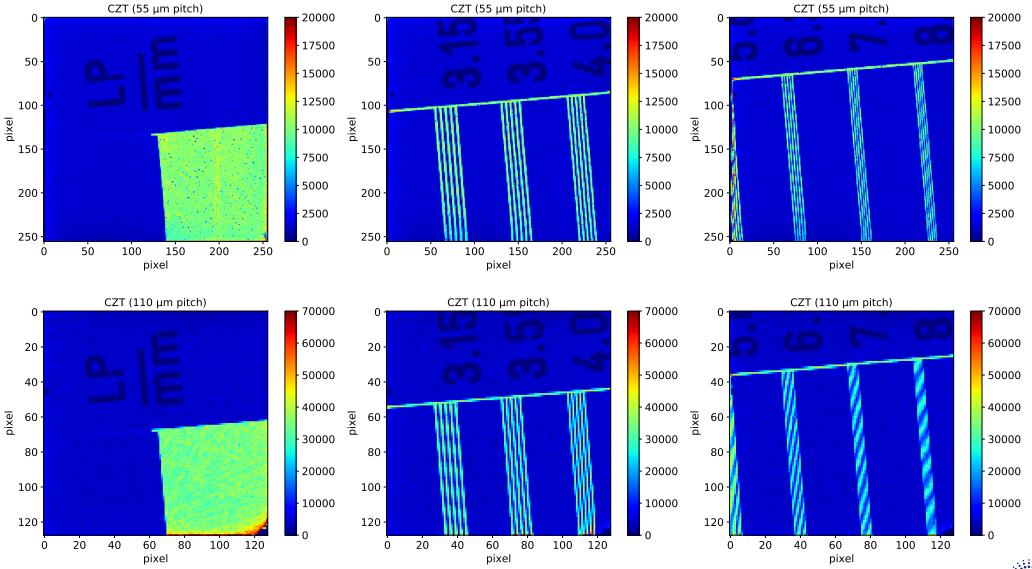


About 3h later...



Imaging performance and spatial characteristics

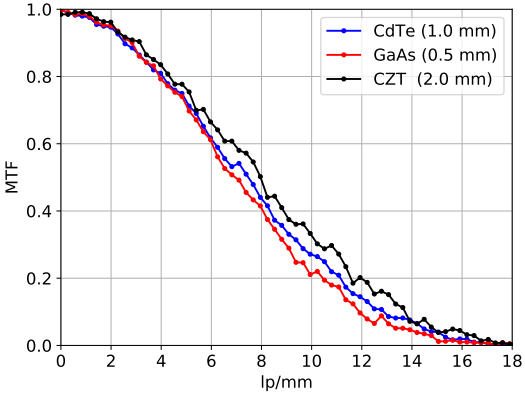


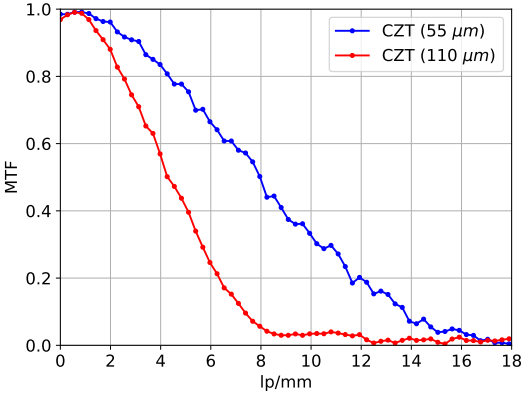


Modulation tranfer function (MTF) - presampling

- Make use of slanted edge method
- Edge/line spread functions (ESF/LSF)

- $LSF(x) = \frac{d}{dx}\{ESF(x)\}$
- $MTF(u) = |\mathcal{F}\{LSF(x)\}|$

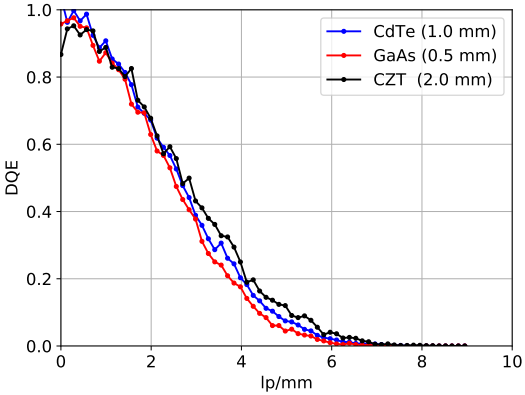


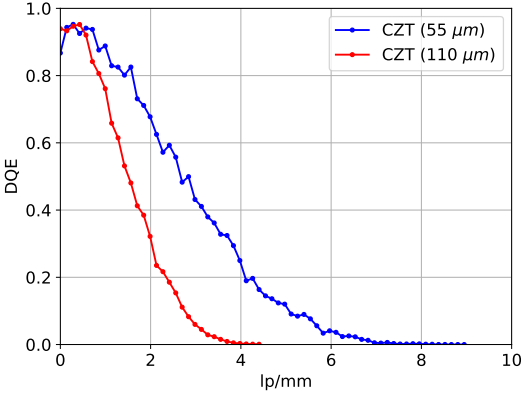


Detective quantum efficiency (DQE)

- Measure of the image quality
- $DQE = \frac{MTF^2}{q \cdot NNPS}$

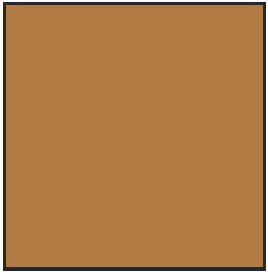
- q: Incident flux per mm^2
- NNPS: Normalized Noise Power Spectrum

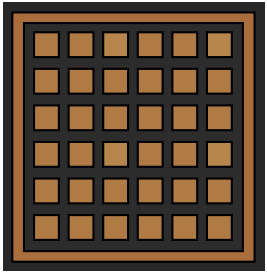


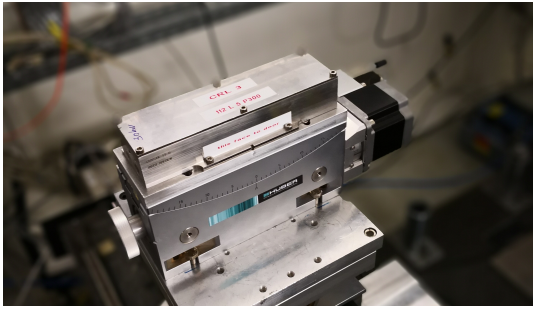


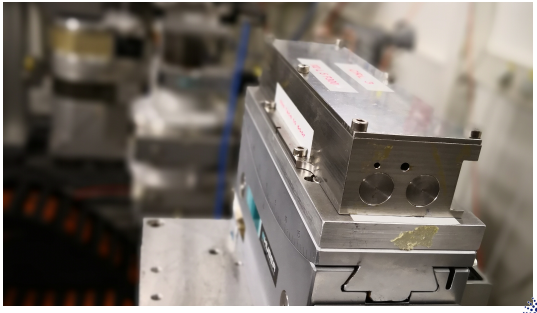
Mesh scans with micro-focused beam

- Be compound refractive lenses
- Beam spot << pixel size
- Precise mapping of a sensor area
- Effective pixel shape



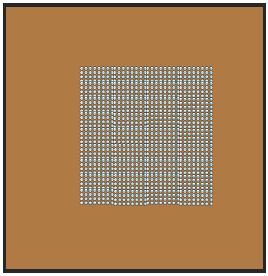


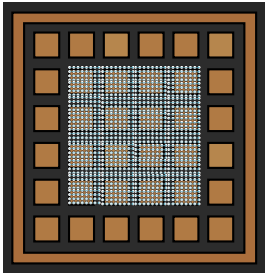


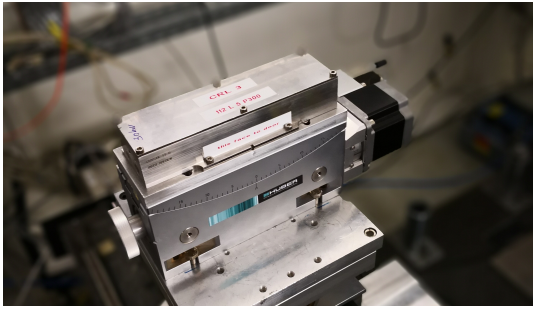


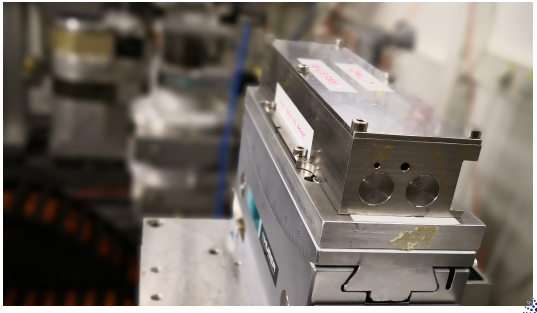
Mesh scans with micro-focused beam

- Be compound refractive lenses
- Beam spot << pixel size
- Precise mapping of a sensor area
- Effective pixel shape



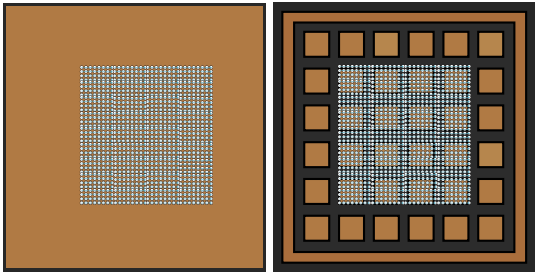


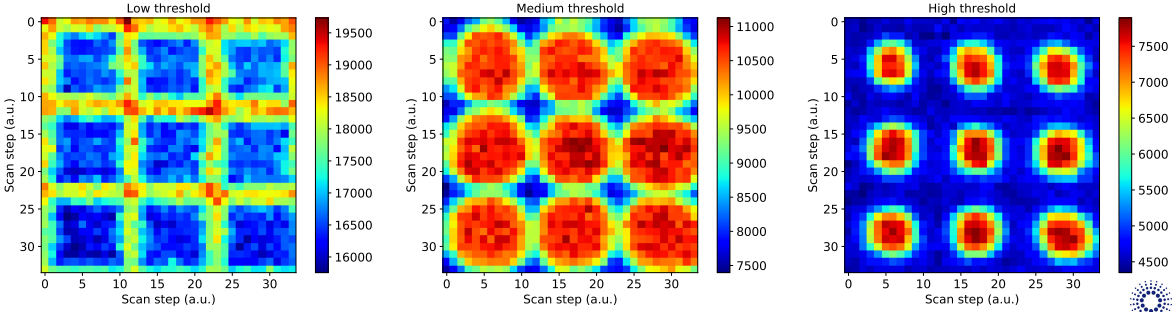




Mesh scans with micro-focused beam

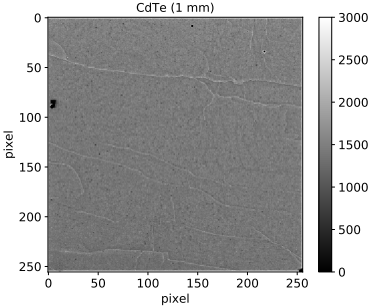
- Be compound refractive lenses
- Beam spot << pixel size
- Precise mapping of a sensor area
- Effective pixel shape

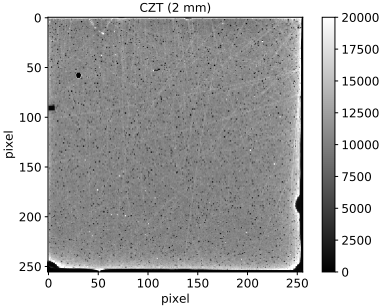


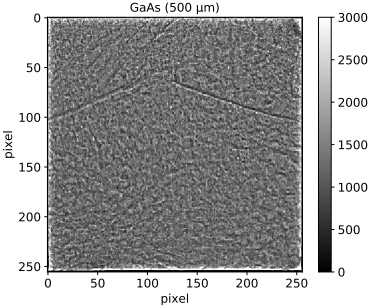


Spation distortions

- Align beam on a visible defect
- Mesh scan surrounding pixels
- Set threshold close to minimum value
- Saturation when beam in inter-pixel area

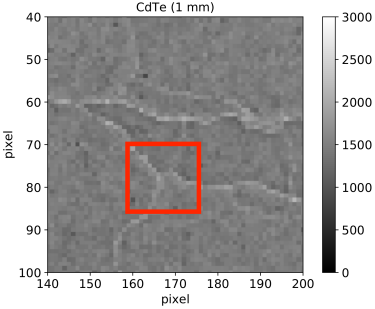


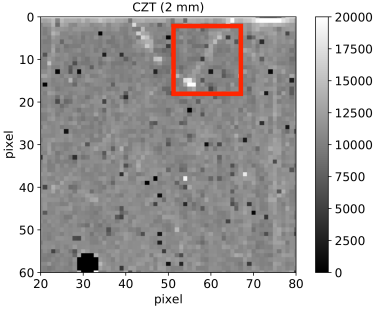


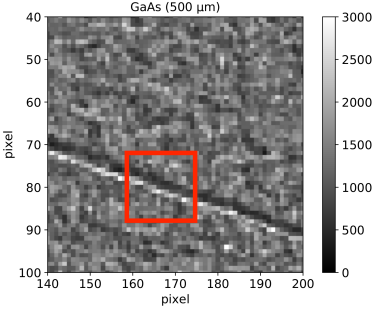


Spation distortions

- Align beam on a visible defect
- Mesh scan surrounding pixels
- Set threshold close to minimum value
- Saturation when beam in inter-pixel area

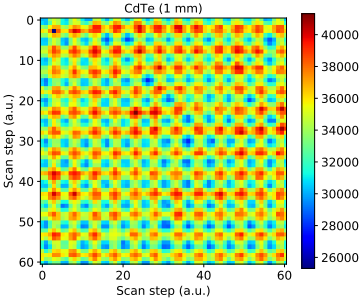


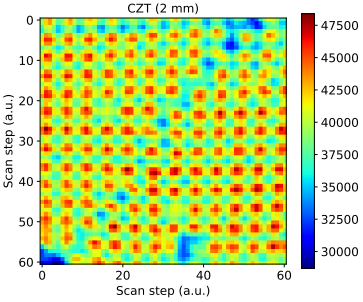


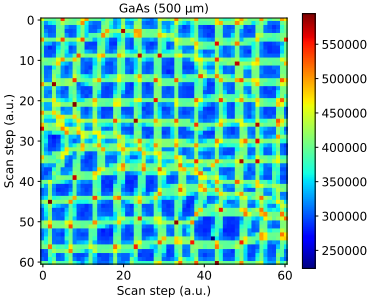


Spation distortions

- Align beam on a visible defect
- Mesh scan surrounding pixels
- Set threshold close to minimum value
- Saturation when beam in inter-pixel area



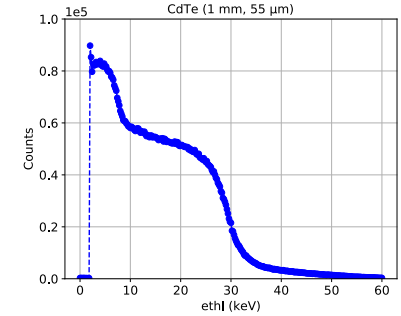


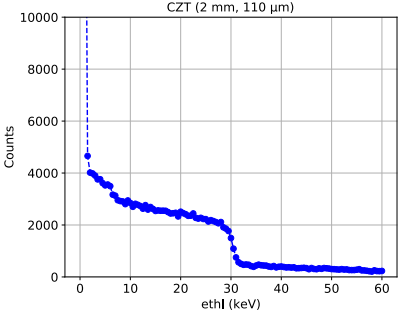


Ref: C. Ponchut et al., 2017 JINST 12 C12023

Threshold scans and single pixel spectra

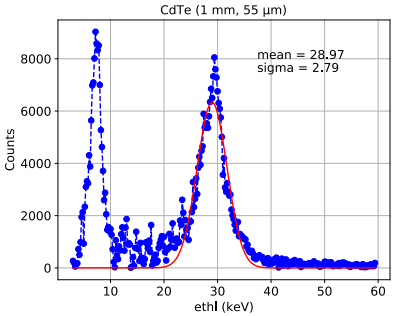
- Align beam at the center of a pixel
- Vary the discriminator threshold
- Measure the number of counts for each threshold step
- The derivative of the threshold scan gives the single pixel energy spectrum
- The peak should correspond with the beam energy

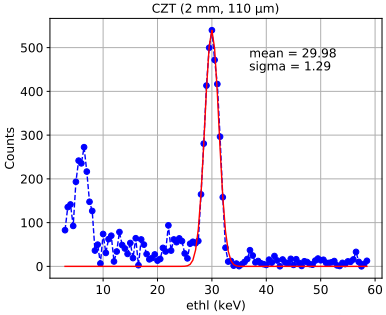




Threshold scans and single pixel spectra

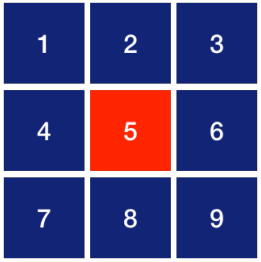
- Align beam at the center of a pixel
- Vary the discriminator threshold
- Measure the number of counts for each threshold step
- The derivative of the threshold scan gives the single pixel energy spectrum
- The peak should correspond with the beam energy

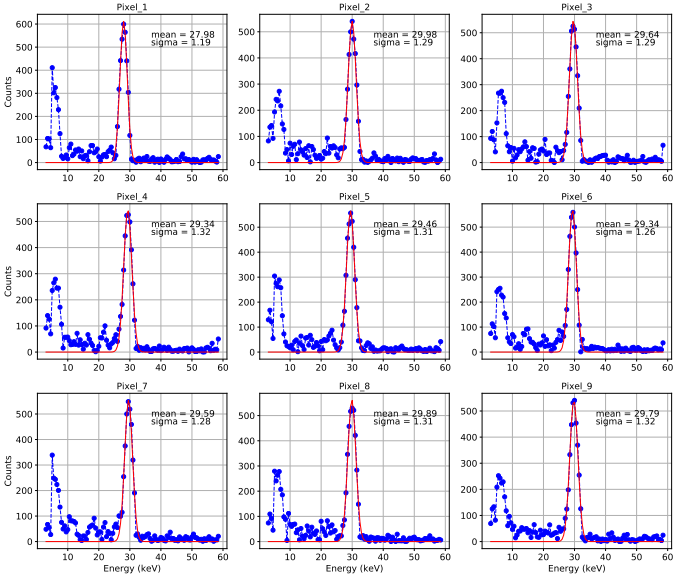




Single pixel spectra of a 3×3 area

- CZT (2 mm, 55 µm)
- Crosscheck for calibration





Outlook

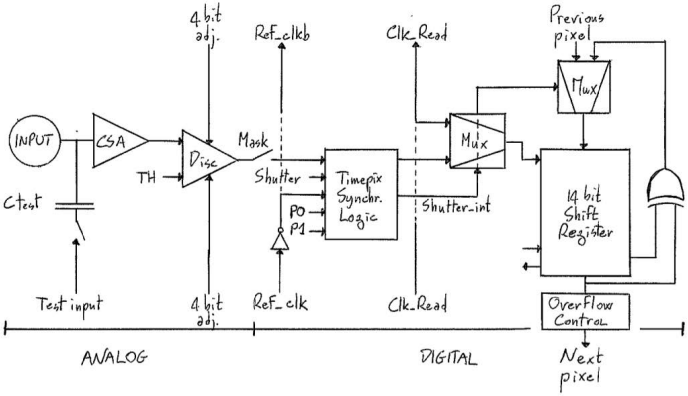
- Shutdown for the EBS Upgrade (since Monday)
- Characterization of high-Z sensors at ESRF
- Preliminary results - Analysis ongoing
- More tests planned at higher energies
  and with more sensors
- The choice of “the sensor” would be a compromise

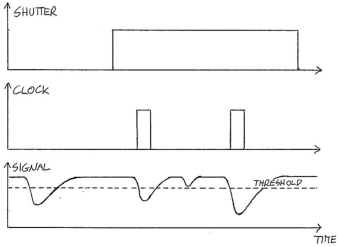
Outlook

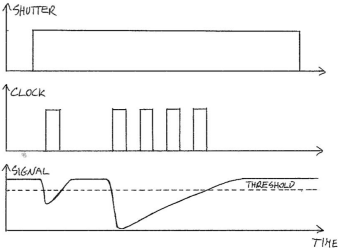
- Shutdown for the EBS Upgrade (since Monday)
- Characterization of high-Z sensors at ESRF
- Preliminary results - Analysis ongoing
- More tests planned at higher energies and with more sensors
- The choice of “the sensor” would be a compromise

Thank you!

Backup


4 bit adj.
Ref_clkb
Clk_Read
Previous pixel
Mux
INPUT
CSA
Disc
Mask
TH
Shutter
Timepix Synchr. Logic
Mux
Ctest
P0
P1
Shutter_int
14 bit Shift Register
Test input
4 bit adj.
Ref_clk
Clk_Read
OverFlow Control
ANALOG
DIGITAL
Next pixel

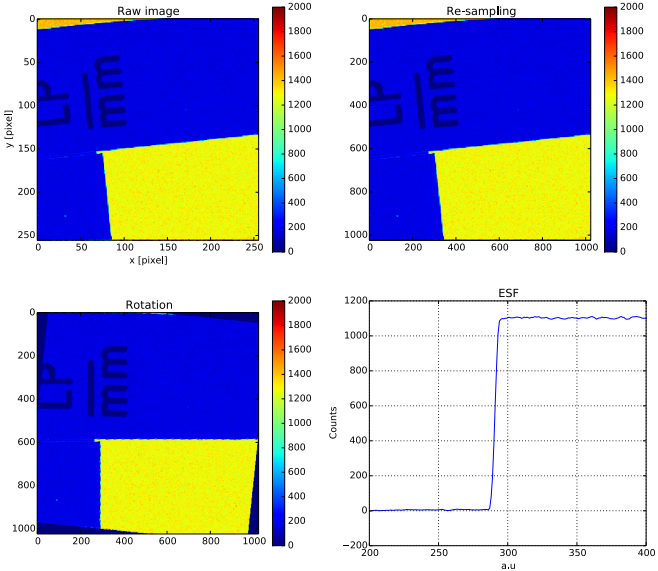

SHUTTER
CLOCK
SIGNAL
THRESHOLD
TIME


SHUTTER
CLOCK
SIGNAL
THRESHOLD
TIME

Backup

- Over-sample image
- Rotate
- Average slices over the edge to obtain ESF
- Differentiate to obtain LSF
- The amplitude of Fourier transform gives the MTF

  $MTF(u) = |DFT_{1D}\{LSF(x)\}|$



Backup

- Noise only image

$$n_i(x,y) = I_i(x,y) - \bar{I}(x,y)$$

- Noise Power Spectrum

$$NPS_{2D}(u,v) = \frac{d_p^2}{N_x N_y} \frac{1}{N} \sum_{i=1}^{N} |DFT_{2D}\{n_i(x,y)\}|^2$$

- Normalised Noise Power Spectrum

$$NNPS_{2D}(u,v) = \frac{NPS(u,v)}{\langle \mathrm{meanpixelsignal} \rangle^2}$$

- Averaging

$$NNPS_{2D}(u,v) \xrightarrow{Averaging} NNPS_{1D}(u)$$