Energy-resolved X-ray imaging method with the counting-type pixel detector

Hidenori Toyokawa

Japan Synchrotron Radiation Research Institute / SPring-8

toyokawa@spring8.or.jp

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Introduction

- Synchrotron radiation science is a part of application using particle accelerators.
- There are many common key technologies about accelerators and also detectors in between high energy physics and synchrotron radiation science.
- In particular, pixel detector technology has desirable features for X-ray imaging too and is ideally suited to overcome the existing imaging plate and CCD-based detector's limitations.
- PILATUS (Pixel apparatus for the Swiss Light Source) has been successfully developed at PSI and SPring-8 has closely collaborated within the PILATUS project since 2001.
- In this study we developed energy-resolved X-ray imaging method with the counting-type pixel detector PILATUS.

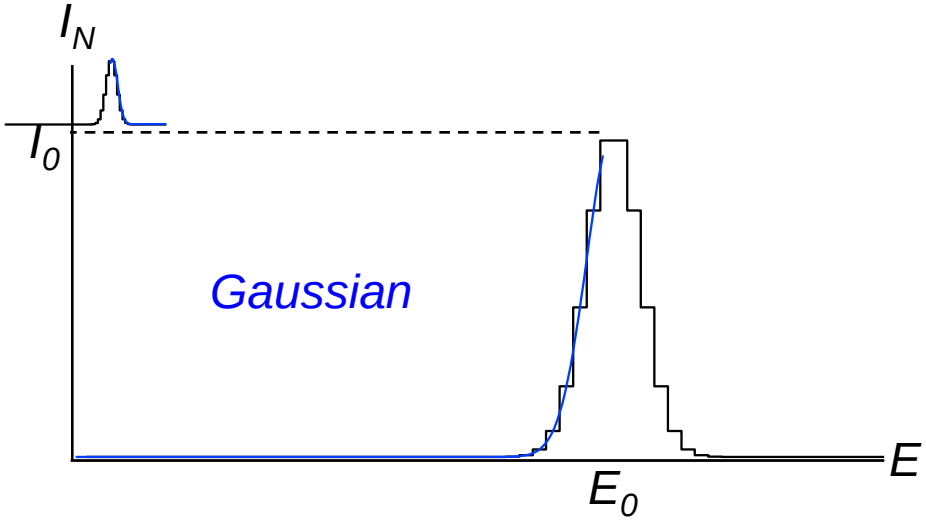
Collaboration between PSI and SPring-8

Counting-type pixel detector

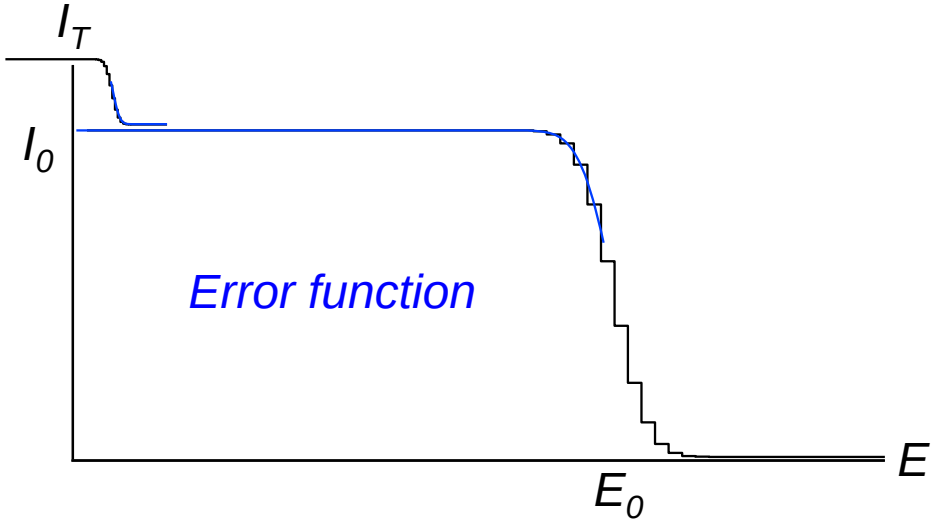
- Standard counting-type pixel detectors like PILATUS contain charge-sensitive amplifier, shape, single or double level comparator and counter.
- This design realizes wide dynamic range, short readout time, high framing rate and excellent point-spread function.
- These unique features have led to novel analysis methods, such as fine ϕ-slicing measurement for macromolecular crystallography, ultra-fast time-resolved X-ray diffraction, depth-resolved XAFS to name a few.

Distribution of normal method and threshold scan

normal energy distribution



threshold scan with lower discri.



$$I_N(E) = I_0 \times exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right)$$

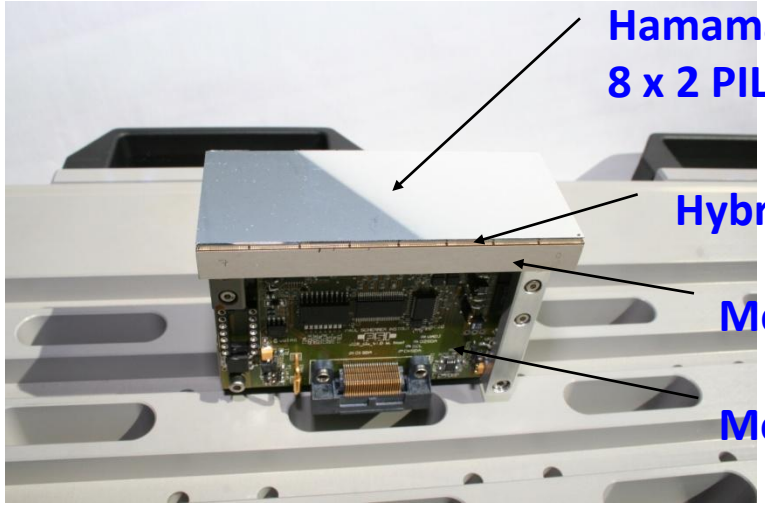
$$I_T(E) = \frac{I_0}{2}\left(1 - erf\left(\frac{E-E_0}{\sqrt{2}\sigma}\right)\right)$$

$$I_N(E) = -\sqrt{2\pi}\sigma \times \frac{\mathrm{d}I_T(E)}{\mathrm{d}E}$$

But threshold scan method is mostly only used for test purposes and calibrations.
In this study we actively apply this technique in X-ray energy measurement.

PILATUS-100K

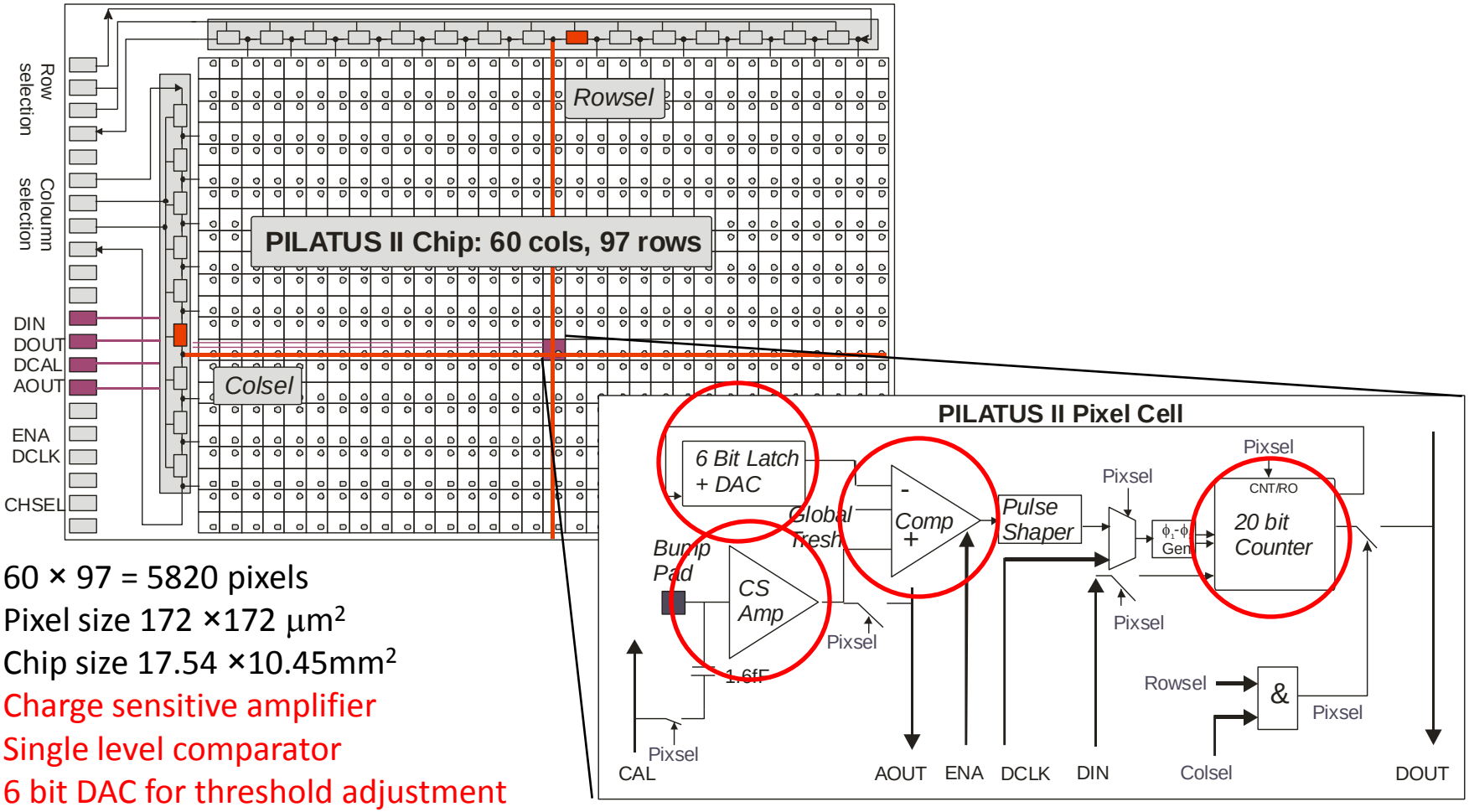
Number of modules	single (8 x 2 chips)
Sensor	Silicon diode array (320 μm)
Pixel size	172 x 172 μm^2
Format	487 x 195 = 94,965 pixels
Area	83.8 x 33.5 mm^2
Dynamic range	20 bit (1:1,046,576)
Dead time	100 – 330 ns
Readout time	2.7 ms
Cooling	Air-cooled
Power consumption	15 W
Weight	4 kg



An array of 8 x 2 CMOS chips is indium bump-bonded to a monolithic silicon sensor.

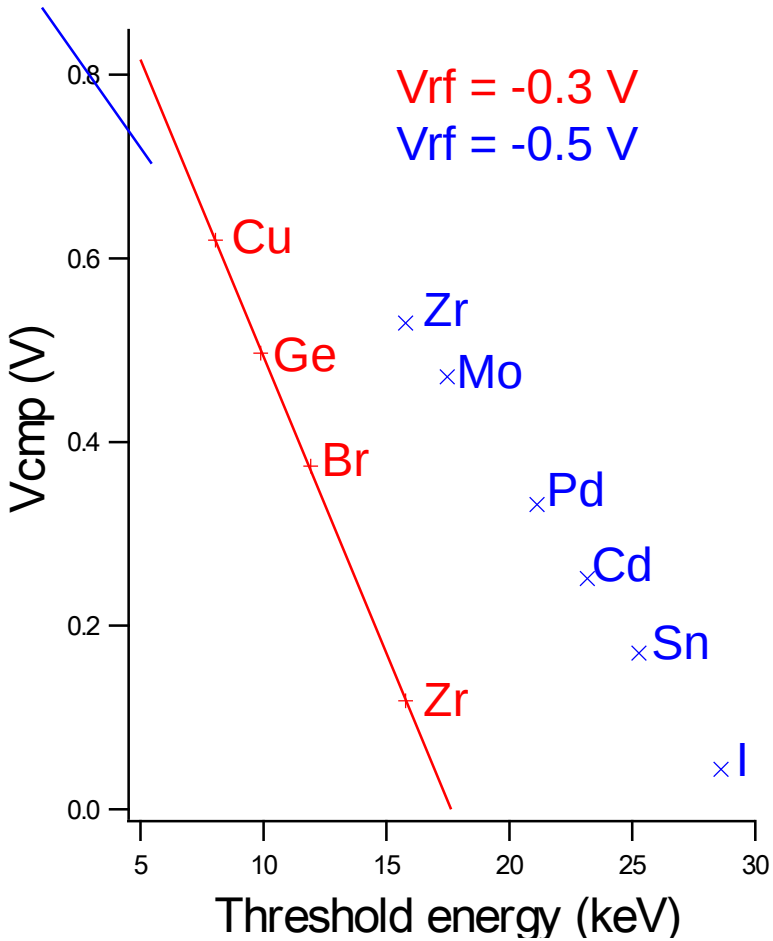
PILATUS-II chip architecture

PILATUS-II chip is designed and fabricated in the UMC 0.25 μm technology using a radiation tolerant design.



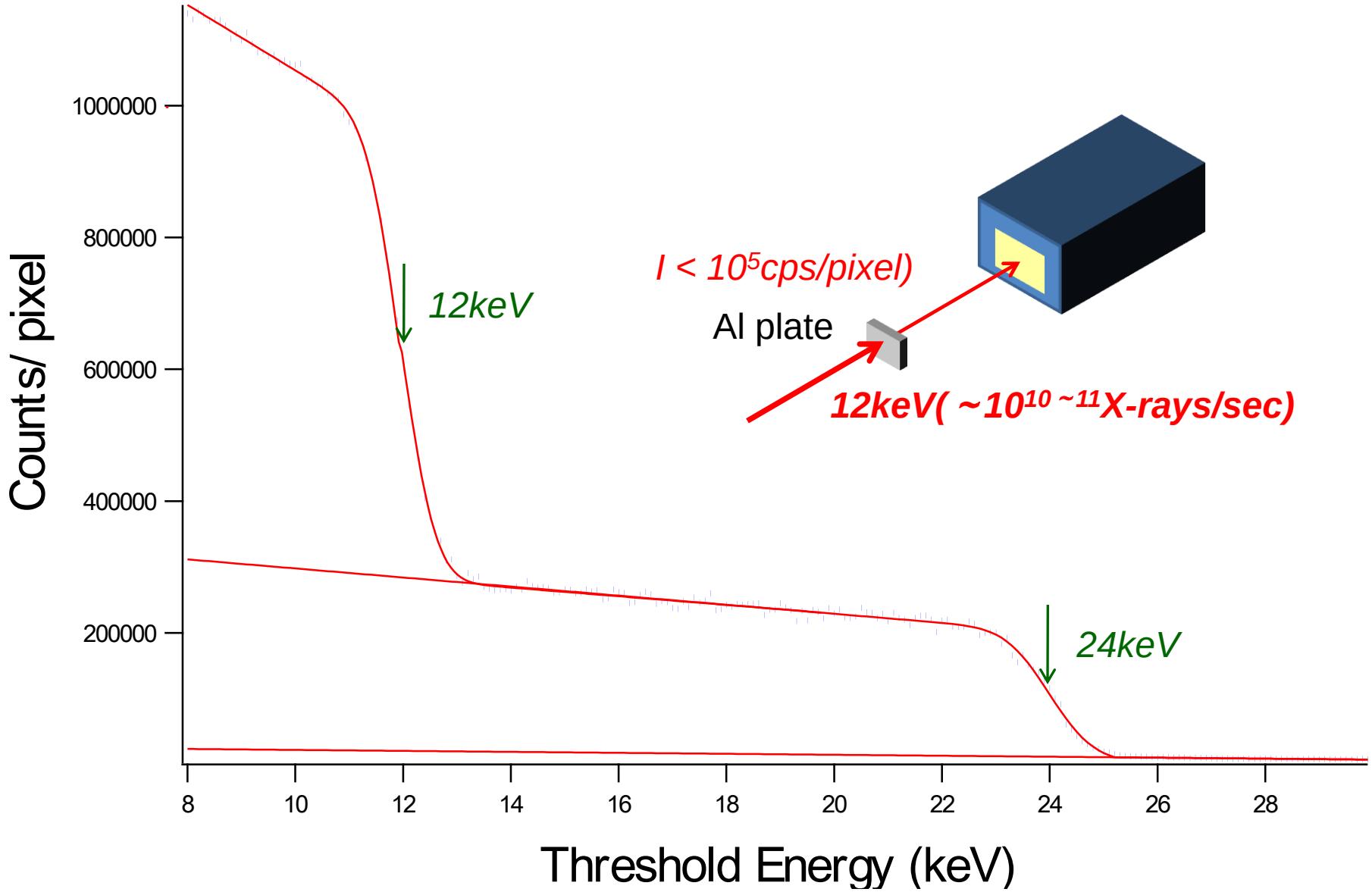
- 60 × 97 = 5820 pixels
- Pixel size 172 ×172 μm²
- Chip size 17.54 ×10.45mm²
- Charge sensitive amplifier
- Single level comparator
- 6 bit DAC for threshold adjustment
- 20 bit counter/pixel (1,048,575 X-rays)

Threshold calibration

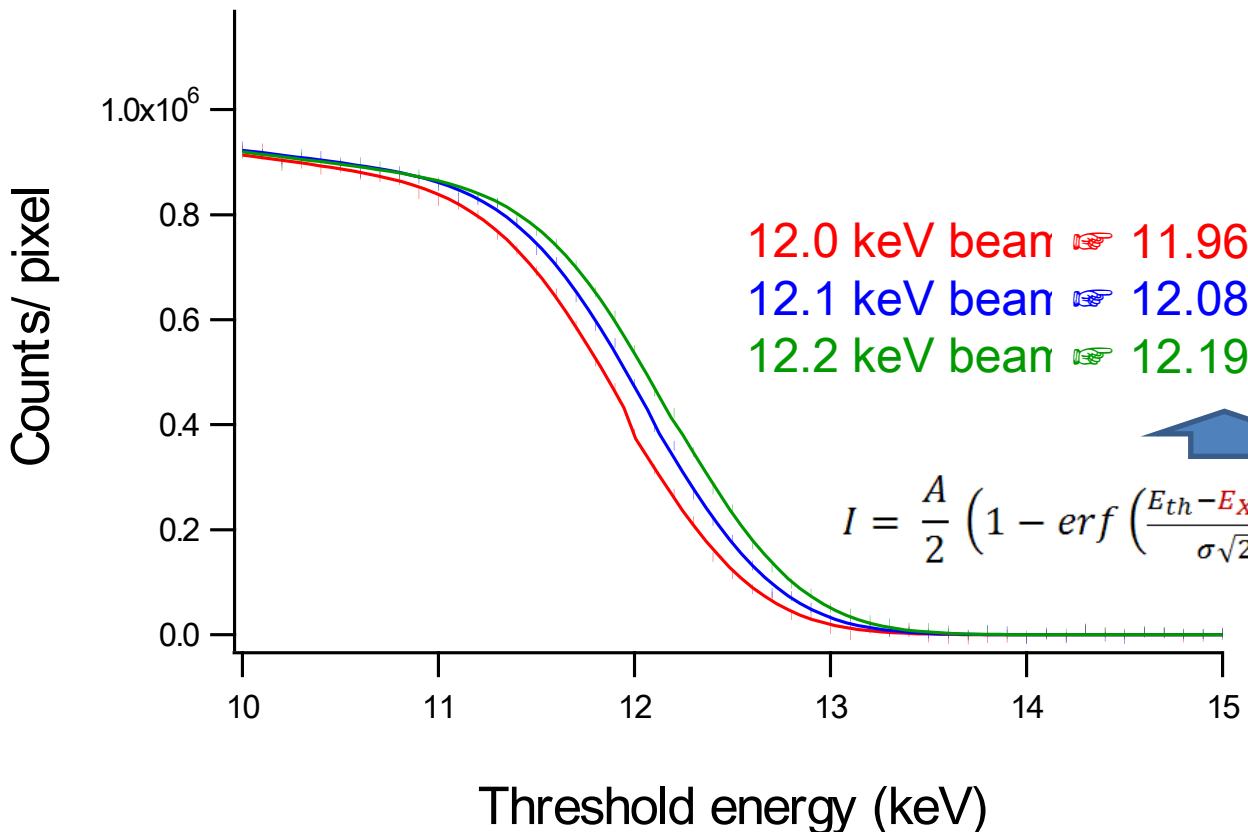


- Thresholds can be controlled with a global threshold commonly applied to all pixels, a global trim voltage and an individually controlled 6-bit DAC for each pixel.
- Threshold settings could be roughly calibrated with test pulse charges, but this procedure led to a warped result because of voltage drops.
- The precise threshold calibrations have been performed with the fluorescent X-ray irradiation from standard samples.
- **The threshold trimming settings depend only weakly on the X-ray energy.**
- **Therefore, any required threshold can be approximated by using the closest trimming setting and scaling the global threshold voltage along the calibration curve.**

Monochromatic beam measurement



Beam energy determination with 100 eV step

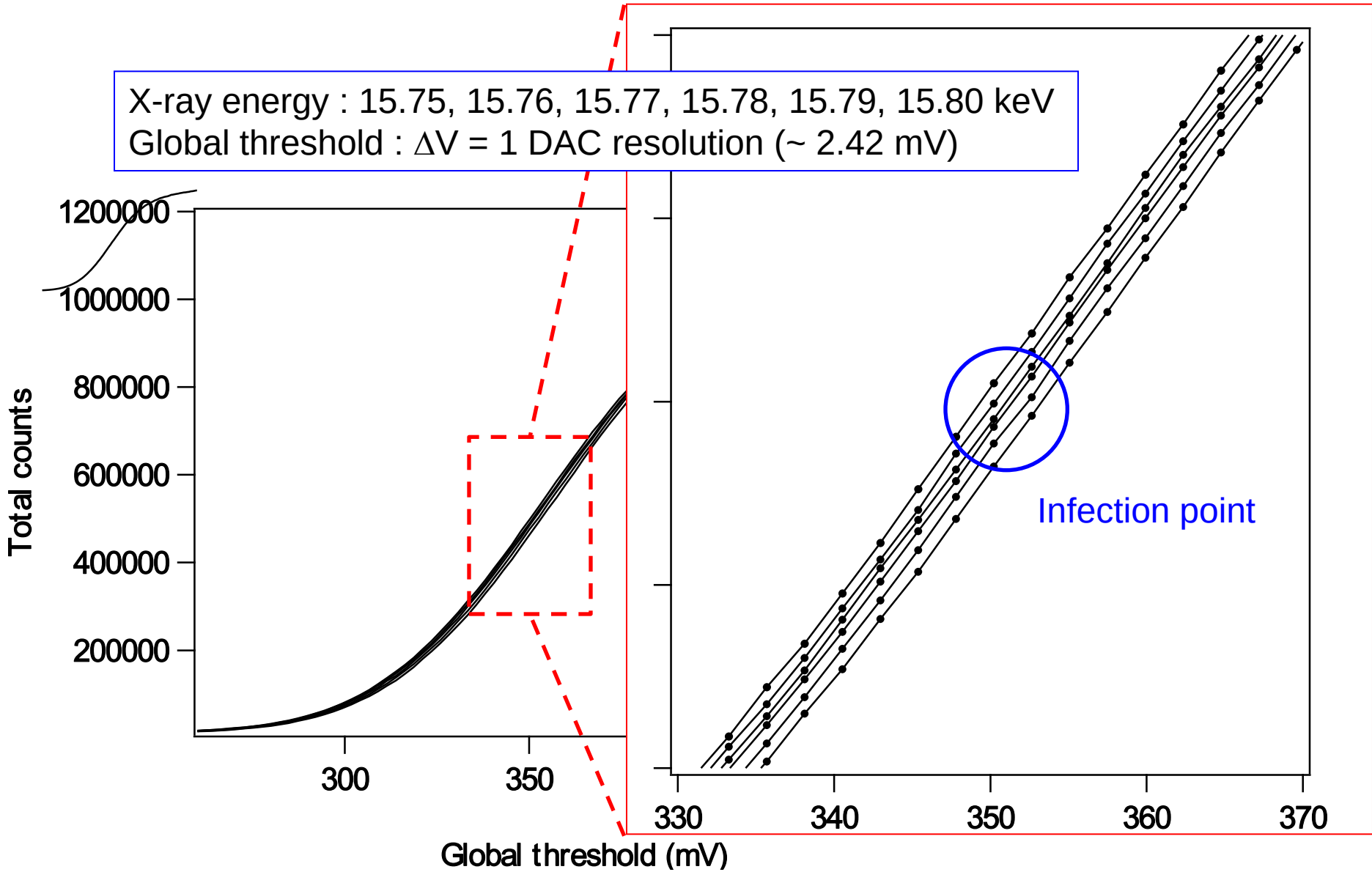


12.0 keV beam ☞ 11.967 ± 0.006 keV
12.1 keV beam ☞ 12.083 ± 0.005 keV
12.2 keV beam ☞ 12.197 ± 0.004 keV

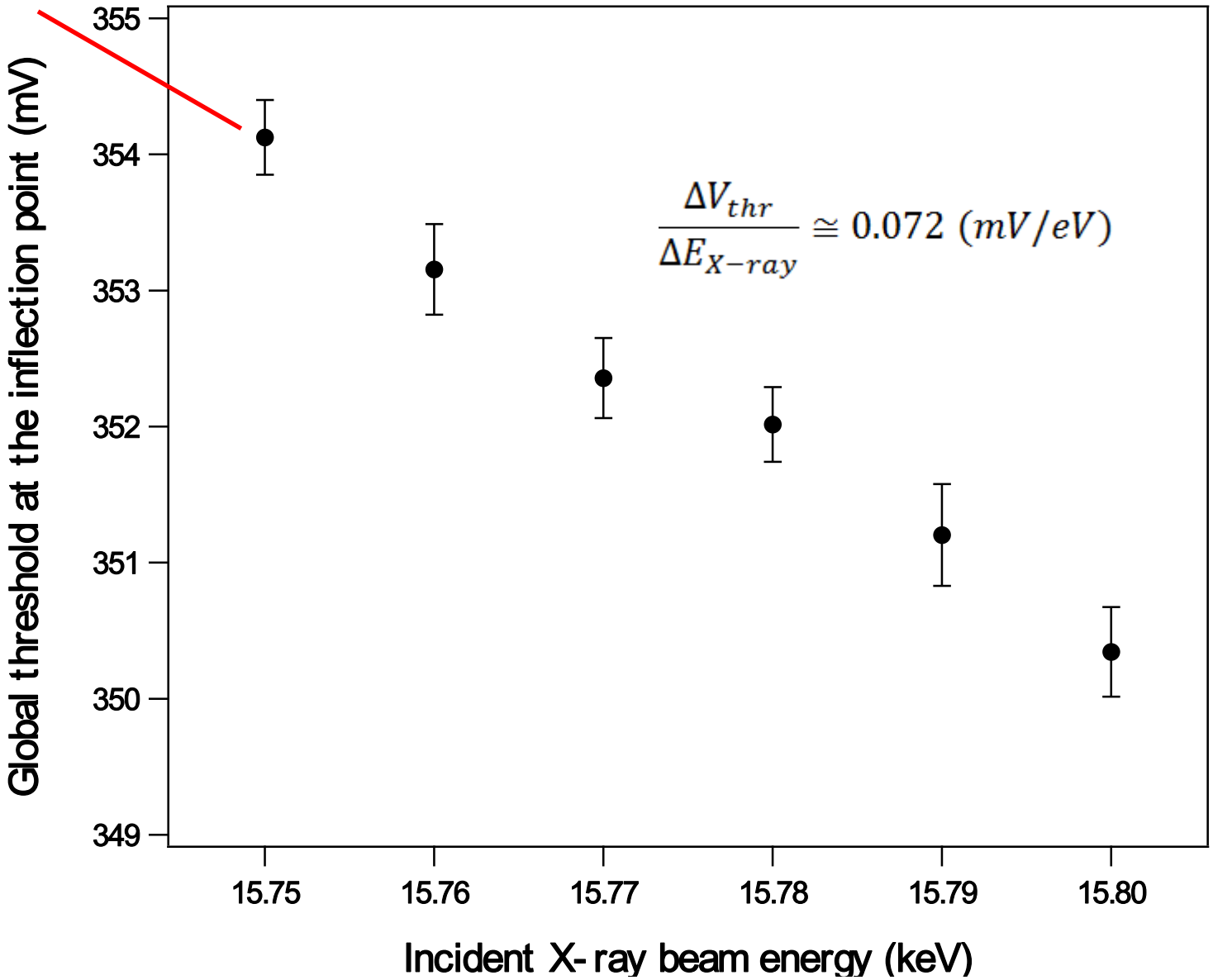
$$I = \frac{A}{2}\left(1 - erf\left(\frac{E_{th} - E_{Xray}}{\sigma\sqrt{2}}\right)\right) + B \times E_{th} + C$$

Beam energy determination with 10 eV step

X-ray energy : 15.75, 15.76, 15.77, 15.78, 15.79, 15.80 keV
Global threshold : ΔV = 1 DAC resolution (~ 2.42 mV)



Error function fitting results

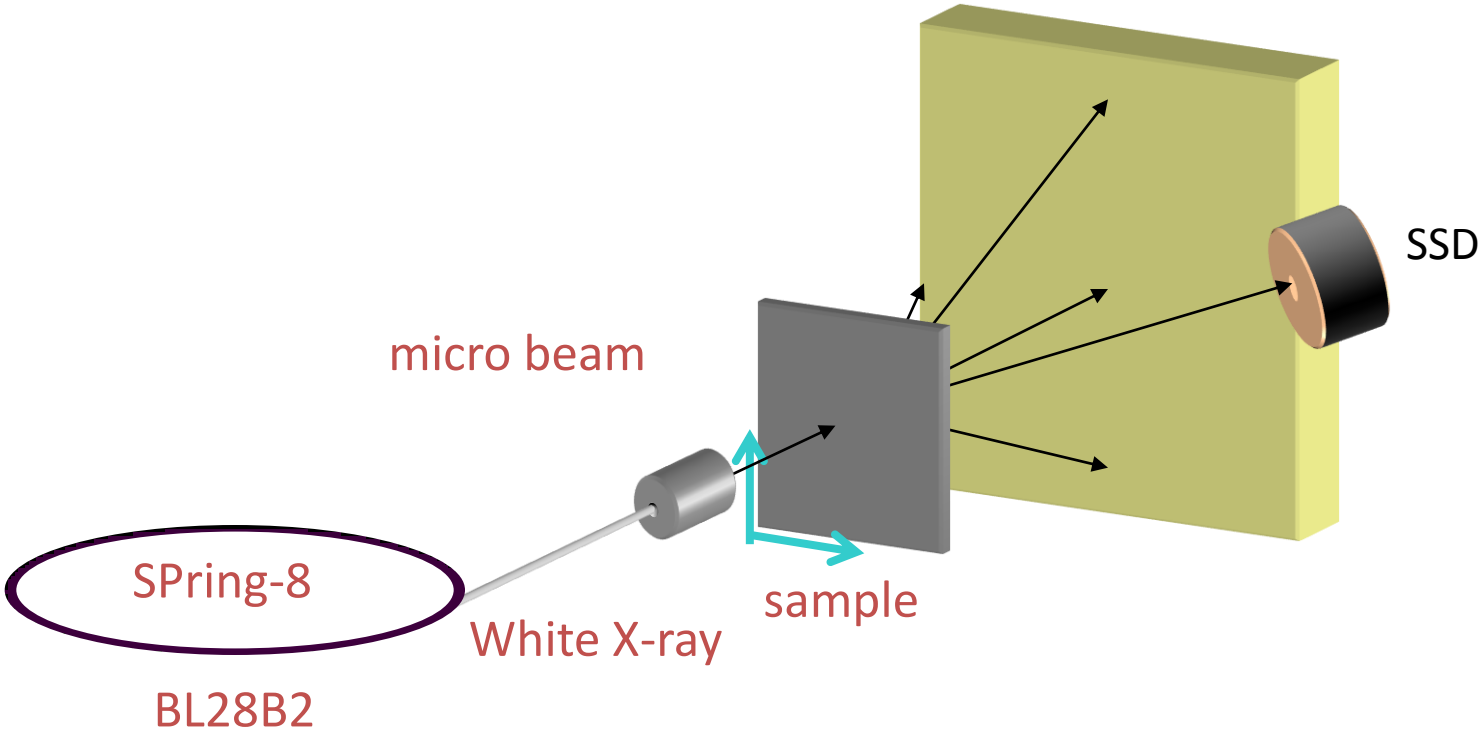


Color Laue method

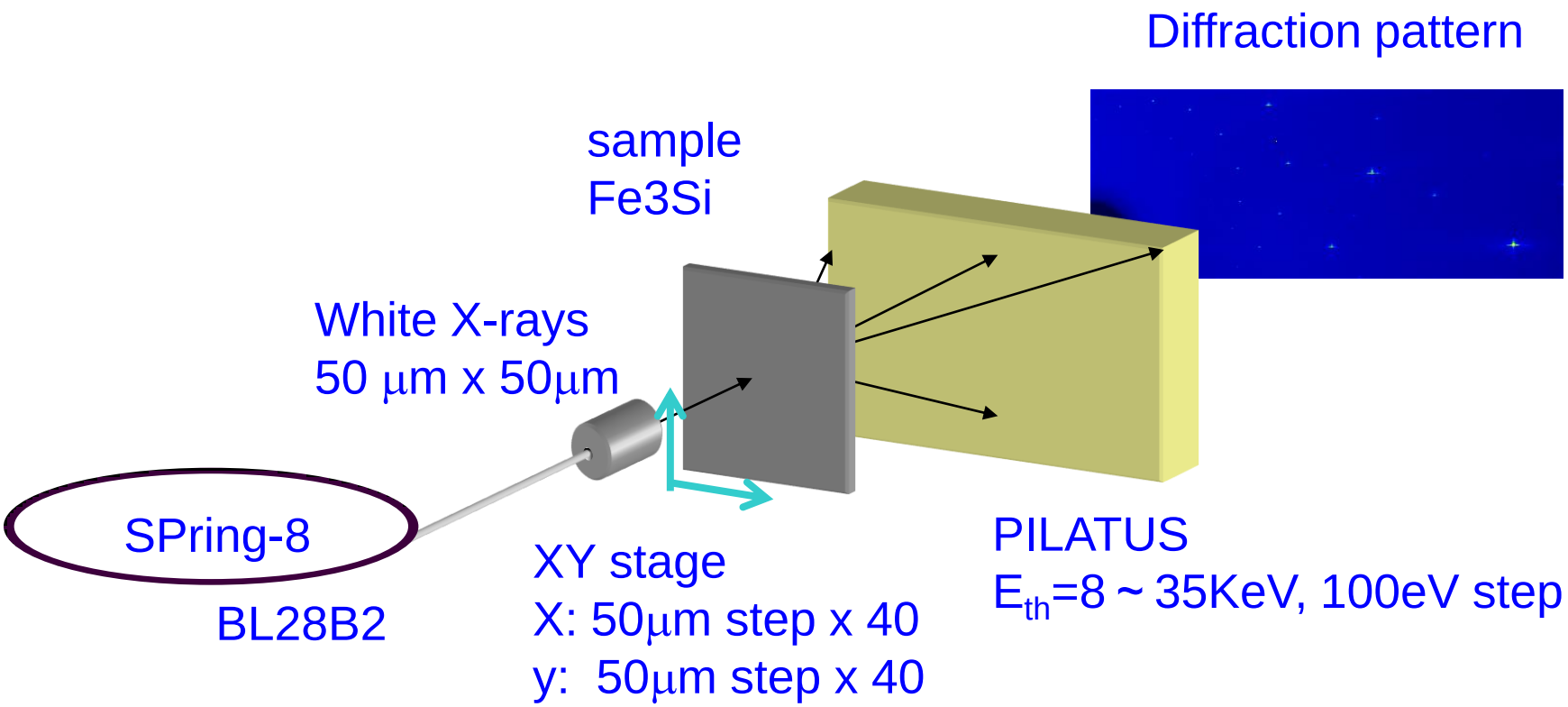
- Laue method is a traditional technique for the X-ray crystallography.
- A sample crystal is irradiated with white X-ray beams and X-ray reflection spots are obtained symmetrically under certain conditions which satisfy Bragg equation: $n\lambda = 2d\sin\theta$.
- Under the standard method Laue diffraction pattern is usually measured with an integration-type area detector and the indexing of diffraction plane is performed only with diffraction pattern information.
- If λ for each diffraction spot is measured in addition, even an indexing deformed crystal could be feasible and the lattice constant *d* is exactly determined by Bragg equation.
- Especially, *d* determination is important to evaluate stress and strain information in steels.

Possible method with standard detectors

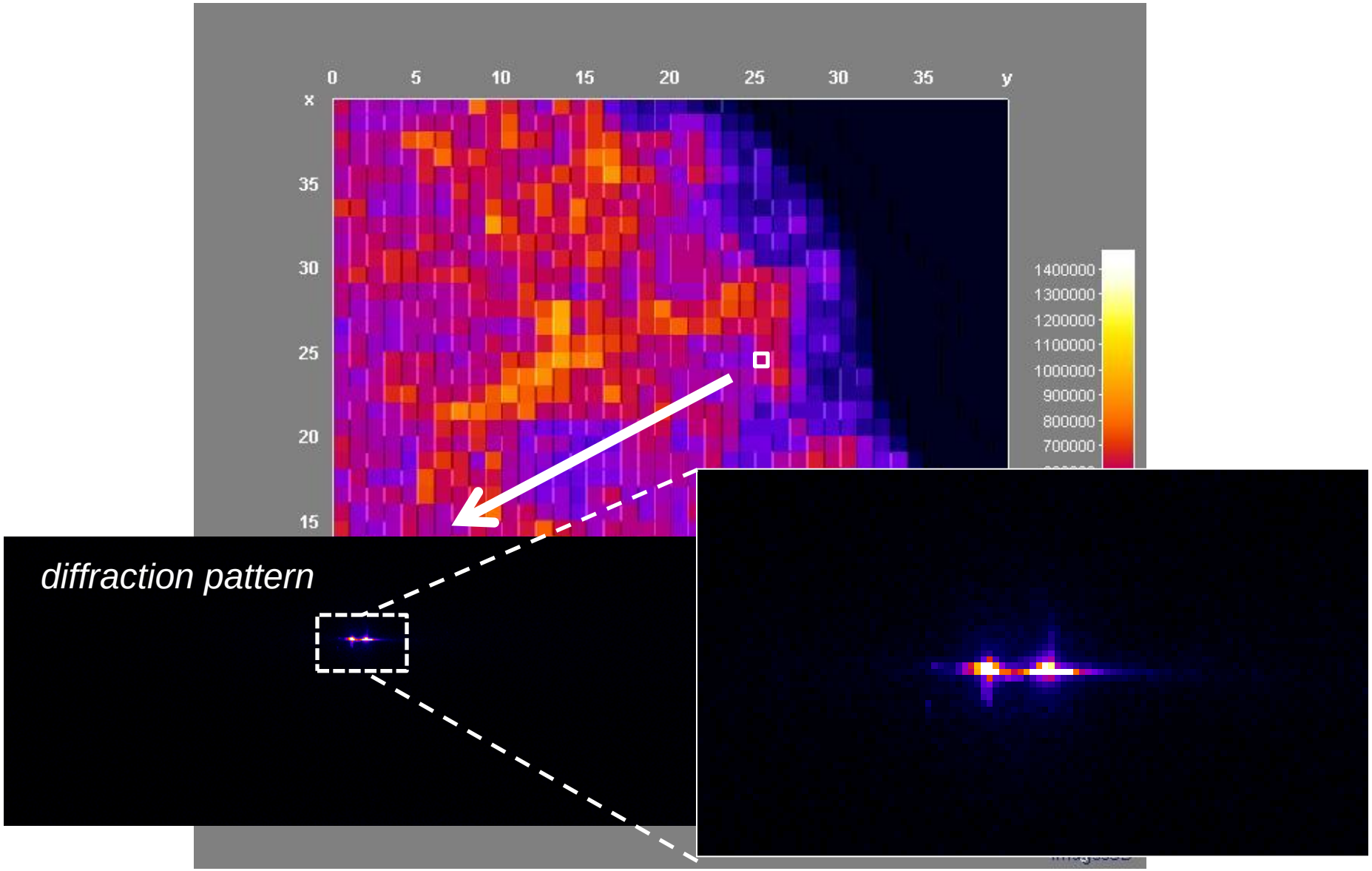
One solution is combine with a standard integration type area detector such as FPD and an energy dispersive point detector of SSD. However, this procedure is so time consuming and complicated.



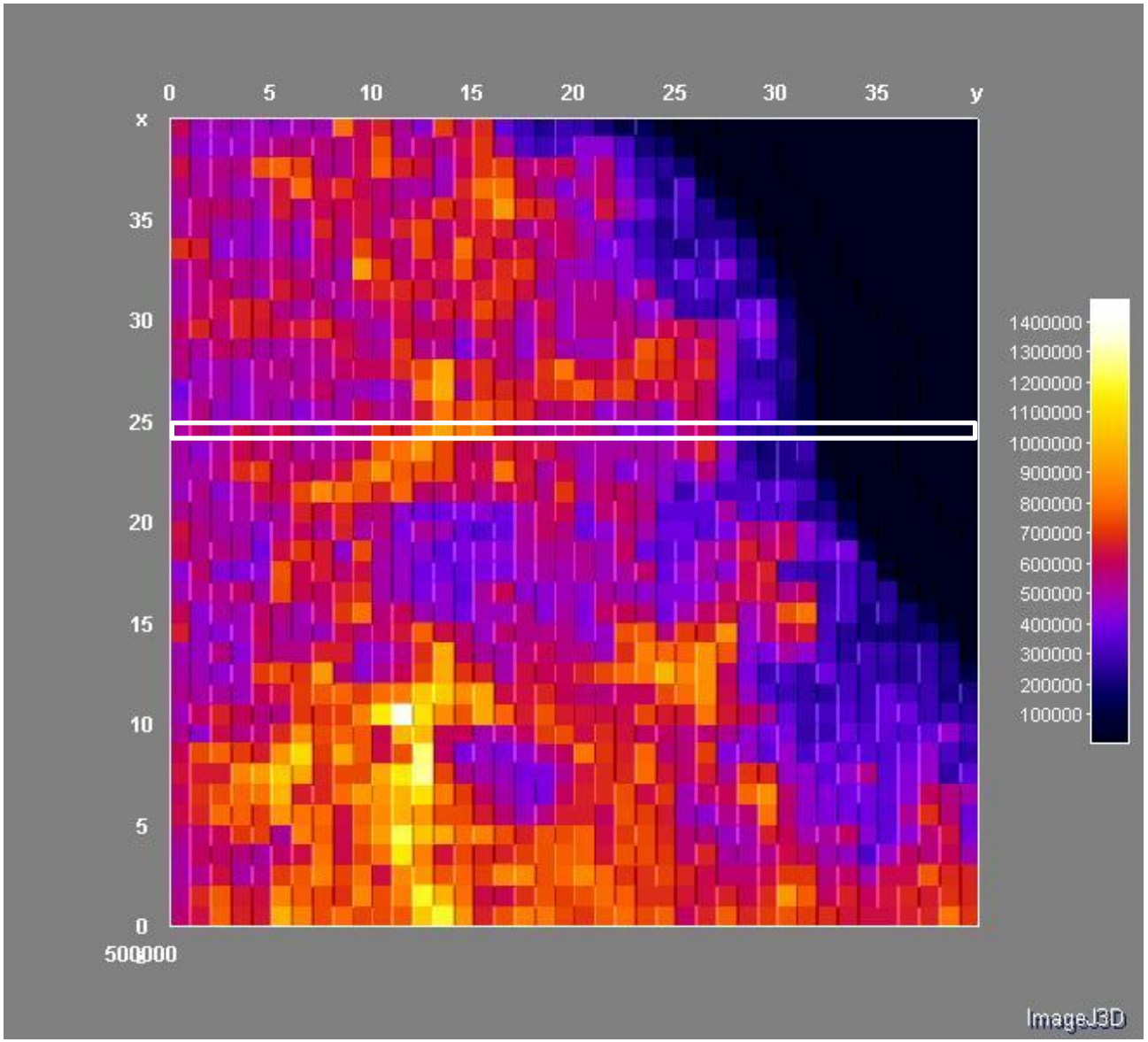
Threshold scan method with counting-type pixel detector



2D intensity plot for Fe3Si grain



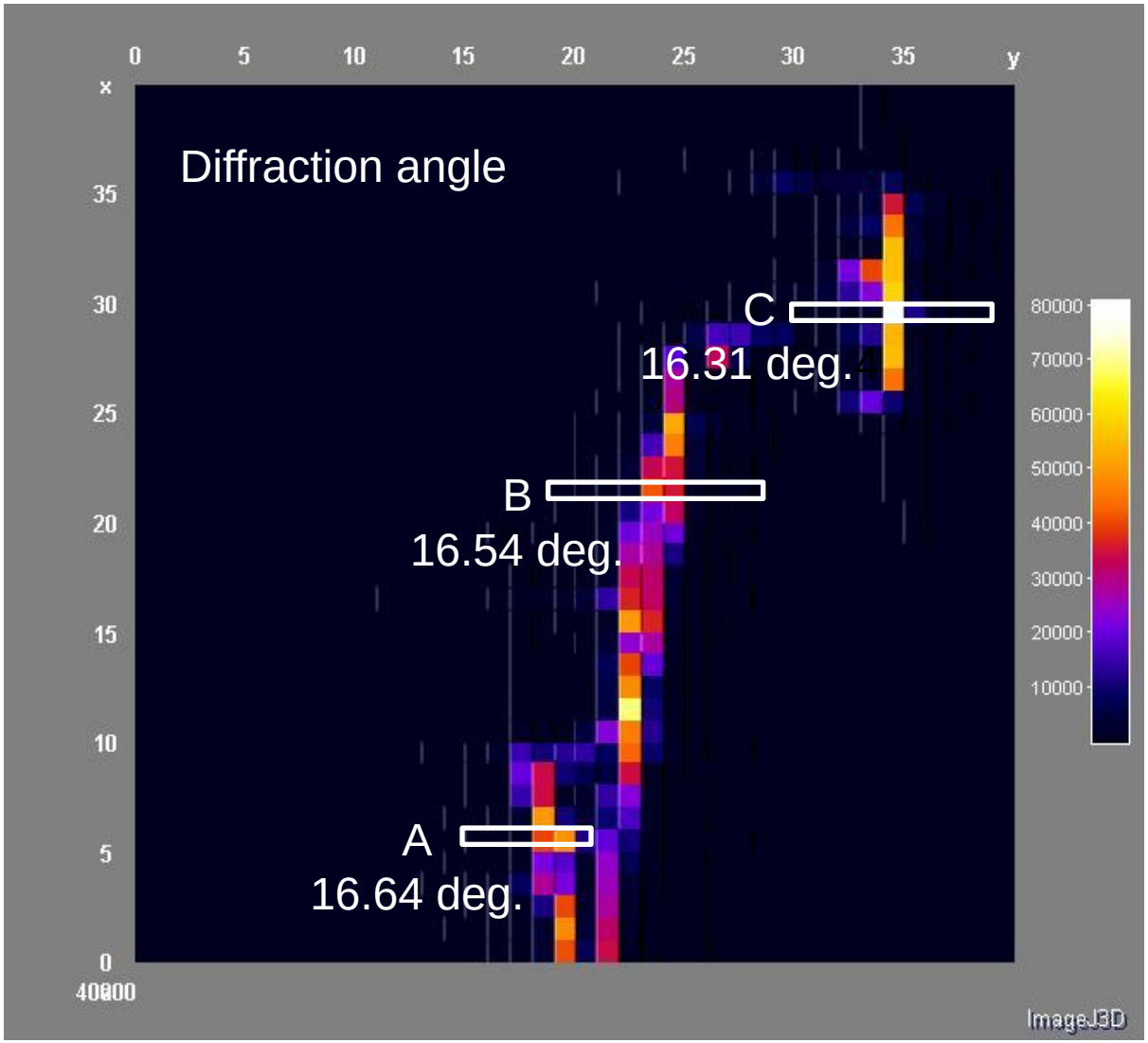
2D intensity plot for Fe3Si grain



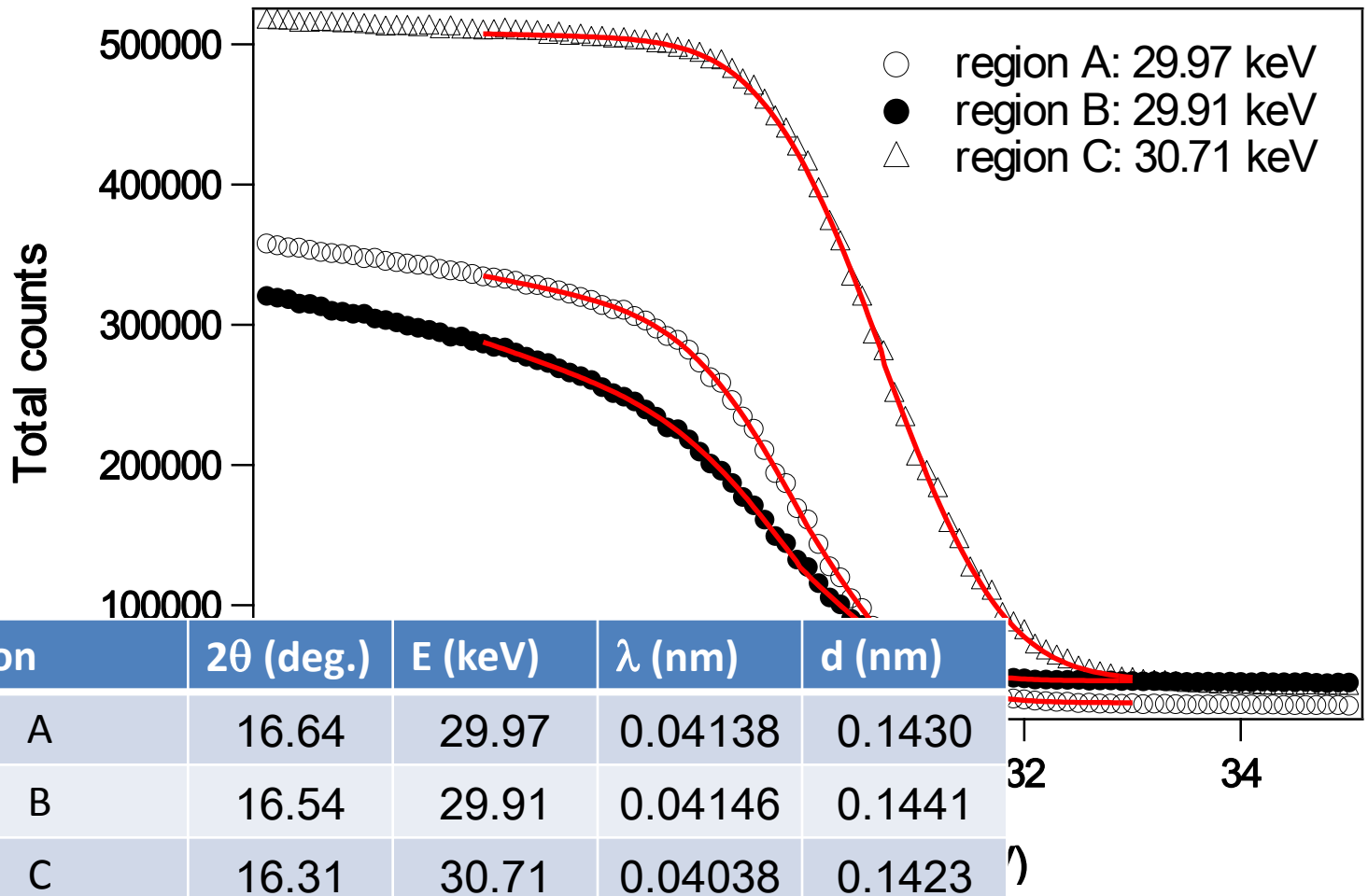
Intensity profile on X-axis vs Scan position

Intensity profile for X-axis on the detector

Sample scan position



Threshold scan for region A, B and C



Region	2θ (deg.)	E (keV)	λ (nm)	d (nm)
A	16.64	29.97	0.04138	0.1430
B	16.54	29.91	0.04146	0.1441
C	16.31	30.71	0.04038	0.1423
Fe3Si (200)				0.143

Summary

- Pixel detector was expected to be a next generation 2D X-ray detector from early stage of 3rd generation synchrotron radiation facilities. Indeed, PILATUS realized X-ray photon counting imaging now and is applying in fast time-resolved X-ray diffraction and so on.
- In this study we developed an energy-resolved X-ray imaging method with counting-type pixel detector, PILATUS.
- Energy determination capability $\Delta E/E$ is attained to less than 10^{-3} around 15 keV region.
- Lattice constant of Fe3Si (200) could be reasonably reproduced with the color Laue method. Further analysis is in progress.
- In order to apply this method in high energy X-ray region, detection efficiency and dynamic range of ASIC must be improved.
- SPring-8 started CdTe pixel detector development for this purpose.