One dimensional detector for X-ray diffraction with superior energy resolution based on silicon strip detector technology

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Motivation I

Si strip detectors are already proved as 1-D detectors for X-ray diffraction

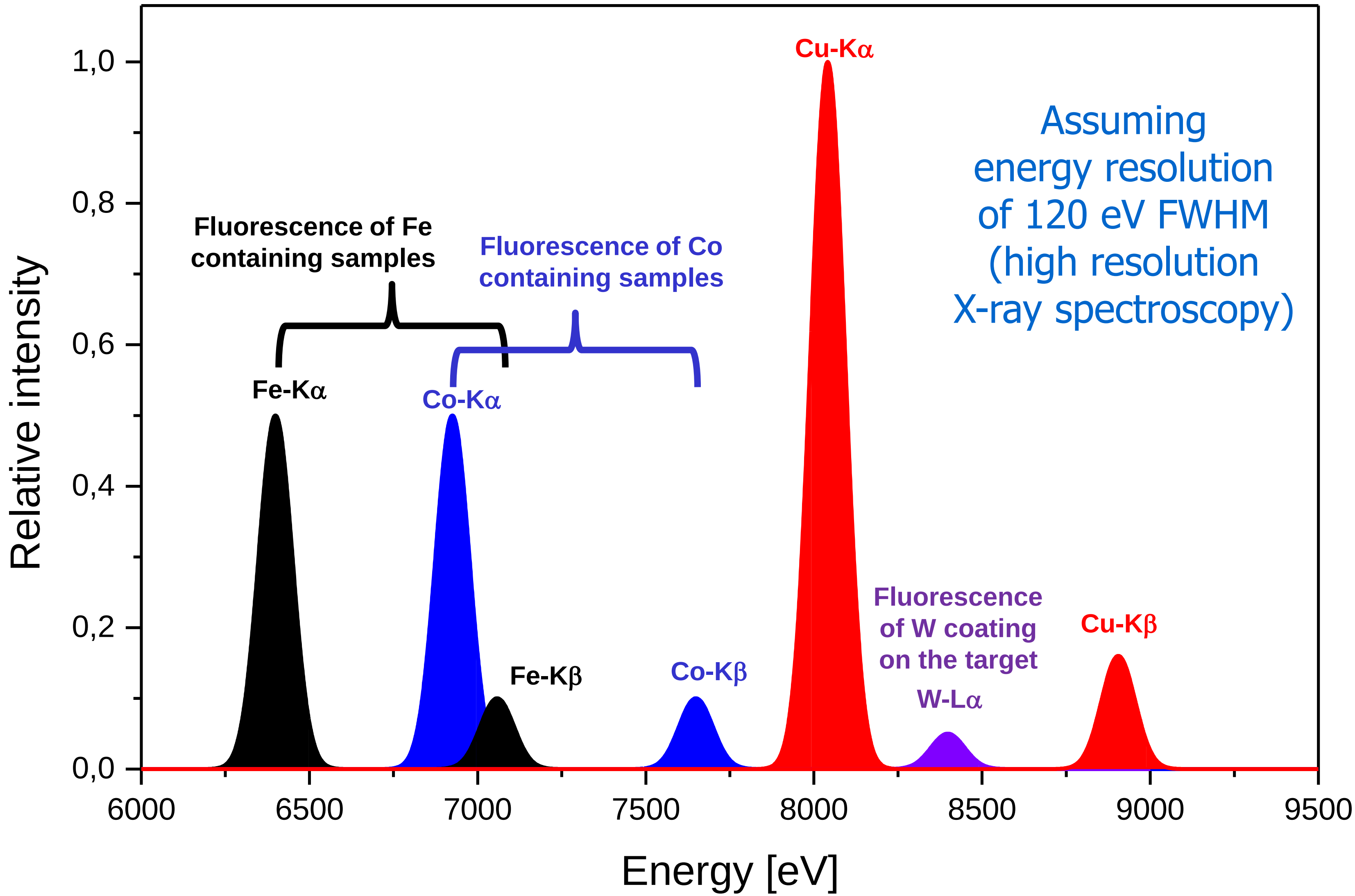
- Silicon strip and CMOS ASICs technology
- Active area 14.4mm × 16mm, 192 Si strips of 75 μm pitch
- Suitable for wavelengths ranging from Cr to Ag radiation (5.4 keV to 22.2 keV)
- Energy resolution ~20% for 8.04 keV
- Max. Count rate, global: $>10^8$ cps
- Max. Count rate, local: $>7\times10^5$ cps
- Dynamic range $> 7\times10^6$ cps per strip
- Can withstand the primary beam
- Angular resolution comparable to a scintillation detector with 0.1 mm receiving slit

Detector "LynxEye" from Bruker AXS

E. Gerndt, et al., Nucl. Instr. and Meth. A 624 (2010) 350–359

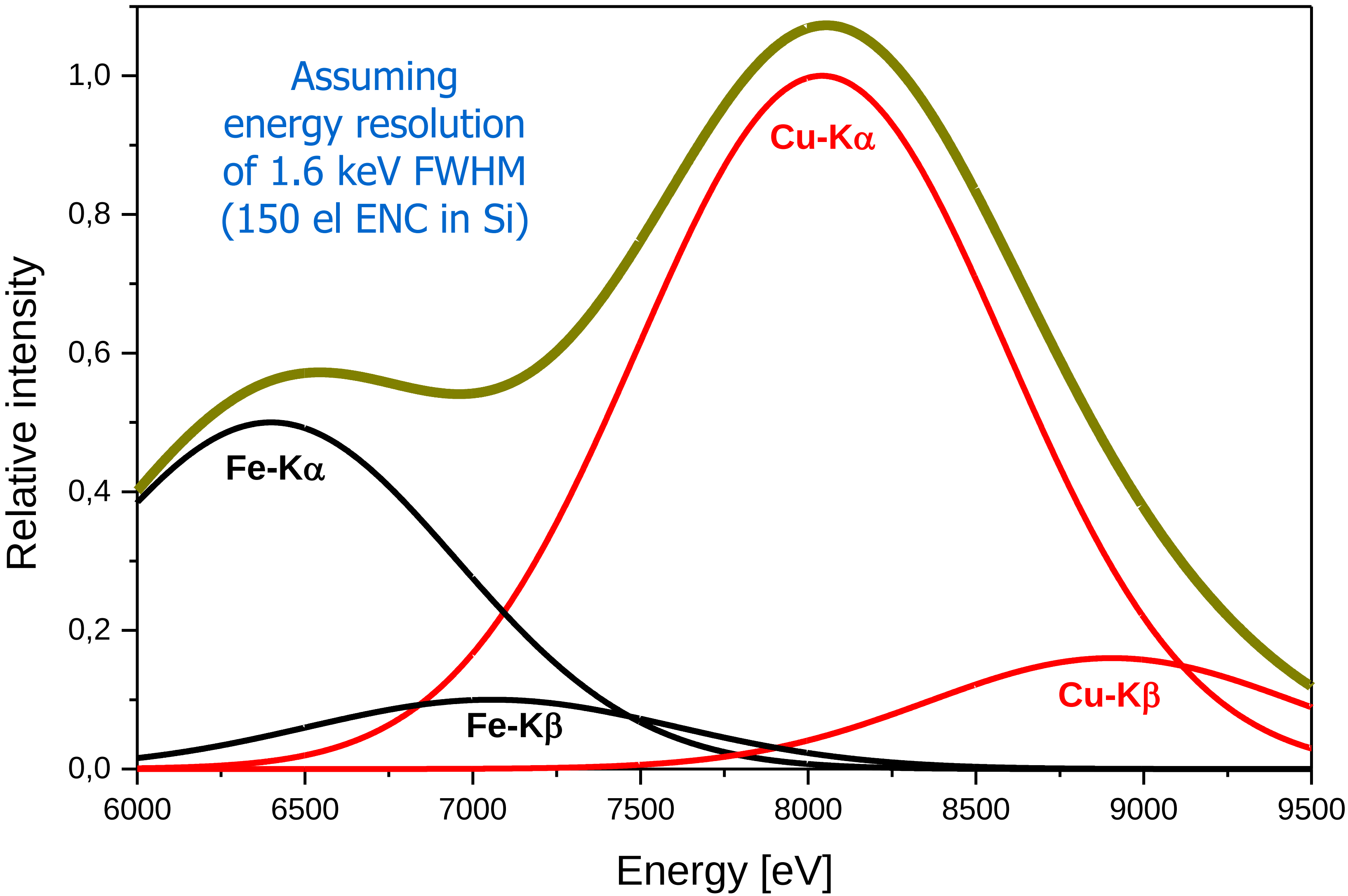
Motivation II

Possible X-ray spectrum in the detector



Motivation III

X-ray spectrum in today's XRD detectors

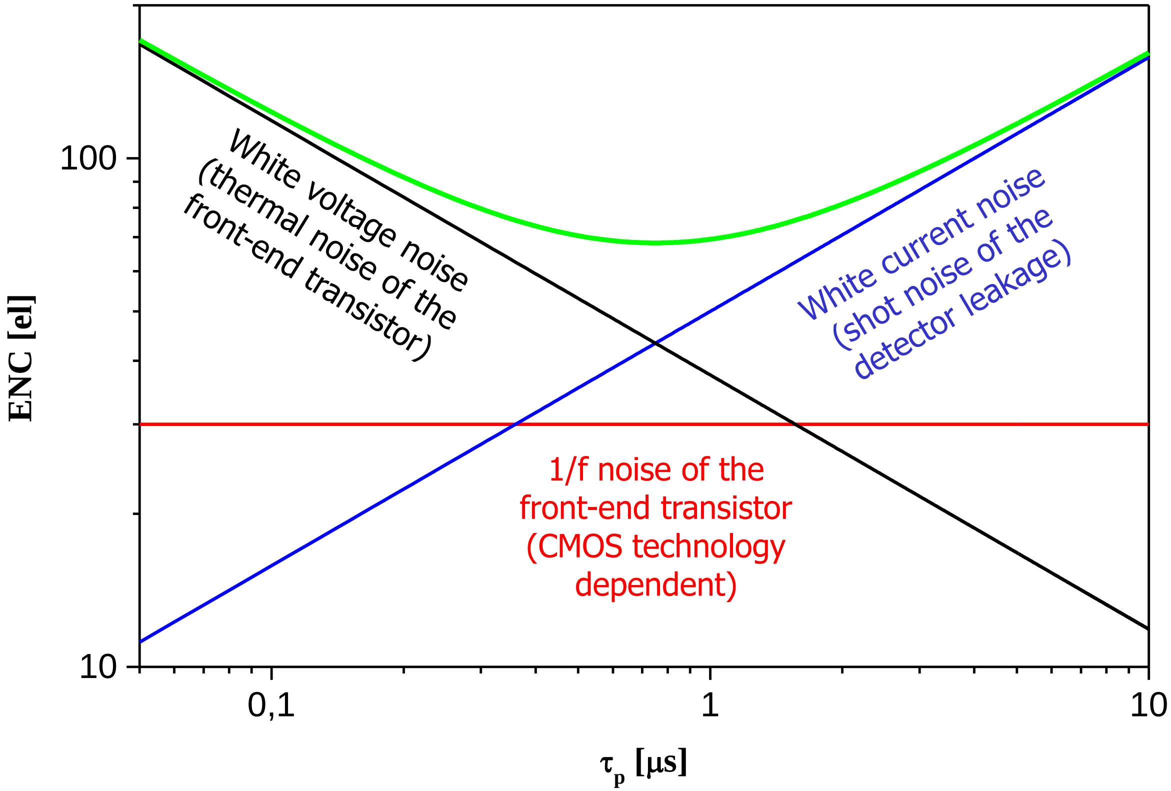


Motivation - summary

- **Reasons for improving energy resolution**
  - Suppression of fluorescence radiation
  - Better peak/background ratio
  - Optimum intensity without filter
  - No analyzer crystal required
  - Reduced relative noise level
- **State-of-the art**
  - Energy resolution: 15 to 20% FWHM
  - Fluorescence sample with Fe-containing material gives high background
  - Weak peaks cannot be detected
  - Low energy tail costs intensity

Electronic noise

$$ENC = \sqrt{K_i \frac{d\langle i_n^2\rangle}{df}\tau_p + K_v \frac{d\langle v_n^2\rangle}{df}\frac{C_{total}^2}{\tau_p} + \frac{A_f}{f}C_{total}^2}$$



How to reduce electronic noise further?

C_{total} (detector granularity)
strips => pixels

Temperature

- effective for reducing detector leakage current

$$\frac{d\langle i_n^2\rangle}{df} = 2qI$$

- not very effective for reducing voltage noise

$$\frac{d\langle v_n^2\rangle}{df},\ A_f \propto T$$

Baseline fluctuations

Assuming ac coupling between the amplifier and teh discriminator
(for practical design reasons)

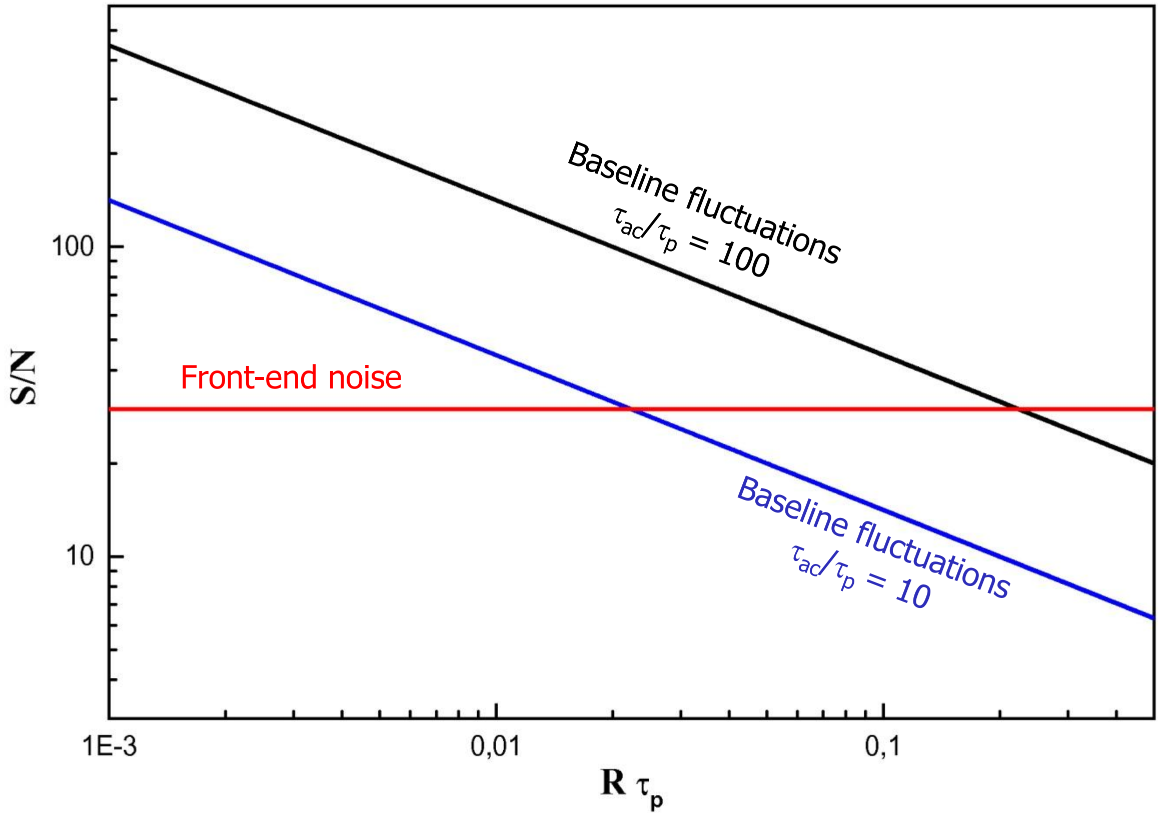
Assume: X-rays of 8 keV (2200 el in Si) and ENC of 80 el rms: S/N = 27.5 τ_{ac}/τ_p = 10, 100

$$\frac{S}{N} \approx \sqrt{2\frac{\tau_{ac}}{\tau_p}\frac{1}{R\,\tau_p}}$$

R – rate

τ_{ac} – time constant of the ac coupling circuit

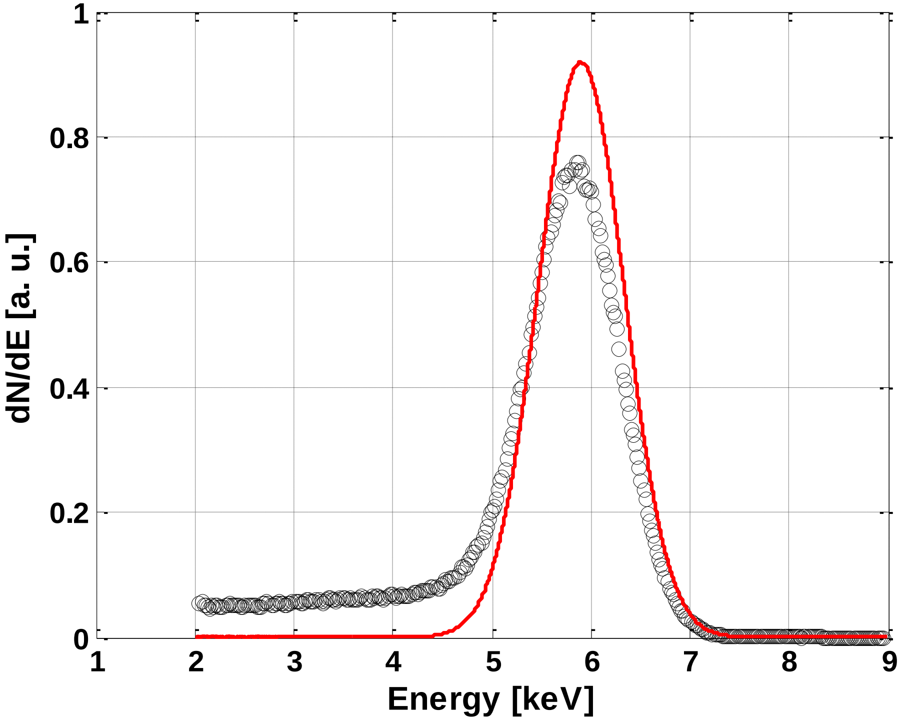
τ_p – time constant of the shaping circuit



Energy resolution – limitation III

Charge division

A simulation package has been built and verified – helpful for optimizing the strip geometry



Single strip amplitude distribution

Depends on:

- X-ray energy
- detector bias
- strip geometry (strip pitch, strip width)
- irradiation geometry (strip-side vs ohmic-side

Clustering (summing) signals from adjacent strips would result in increased noise by sqrt(2) in case of two strips.

P. Wiacek, W. Dabrowski, Nucl. Instr.and Meth. A 580 (2007) 1355–1362

Requirements for Si strips

Spatial resolution

- defined by the strip pitch assuming binary readout

Charge collection

- strip pitch / strip width => electric field distribution around the strips to minimize charge sharing
- strip-side vs. ohmic-side irradiation
- high bias voltage to minimize charge sharing due to diffusion

Noise

- low leakage current => avoid strong electric field around the strips => wide strips
- small strip capacitance => narrow strips
- high bias resistance => either FOXFET bias or DC-coupled strips

Si strip detector specs

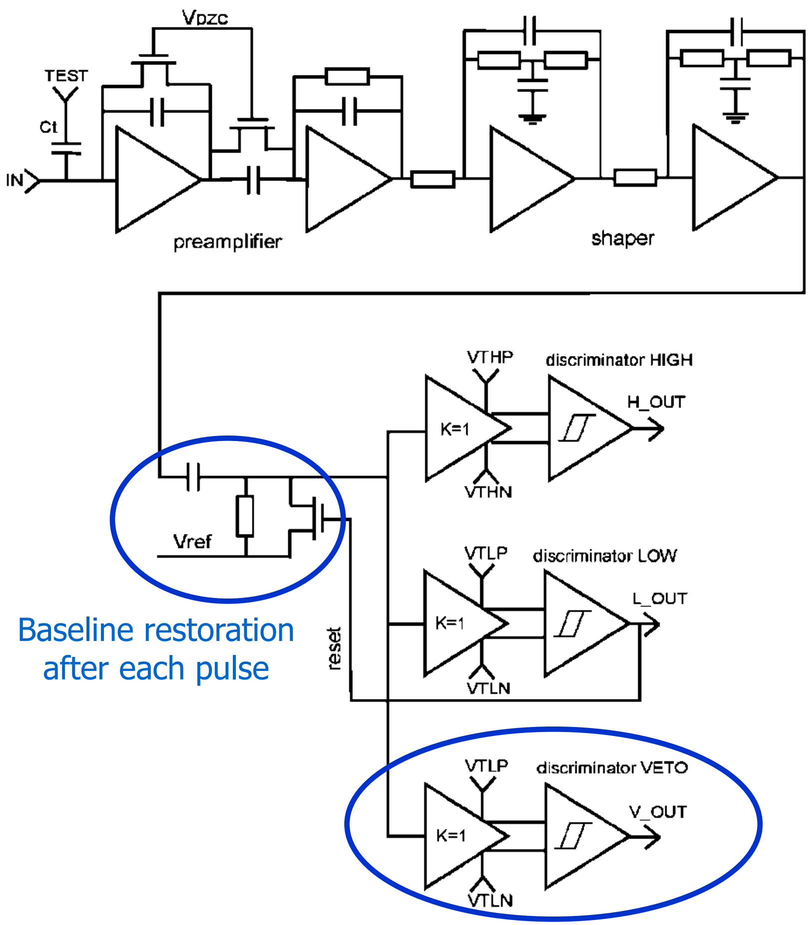
➢ Detector thickness	300 μm
➢ Strip length	16.9 mm
➢ Strip pitch	75 μm
➢ Number of strips	192
➢ DC coupled strips p-in-n	
➢ Strip capacitance to all neighbours	1.25 pF/cm
➢ Strip capacitance to backplane	0.15 pF/cm
➢ Total strip capacitance for 16.9 mm strips	2.4 pF
➢ Max leakage current per strip at 20°C	0.12 nA (10 nA/cm^2)

Readout ASIC – requirements

- Binary readout with window discrimination
- Switchable shaping:
  - ″slow″ (τ_p=1μs) for high resolution resolution applications
  - ″fast″ (τ_p=200ns) for high count rate applications
- Noise, below 80 el rms for slow shaping at room temperature
- Uniformity of gain and discrimination thresholds > input equivalent channel-to-channel spread should be negligible with ENC
- Compensation of the detector leakage current
- Base line restorer
- Interstrip logic to allow rejection of events with significant charge sharing between adjacent strips

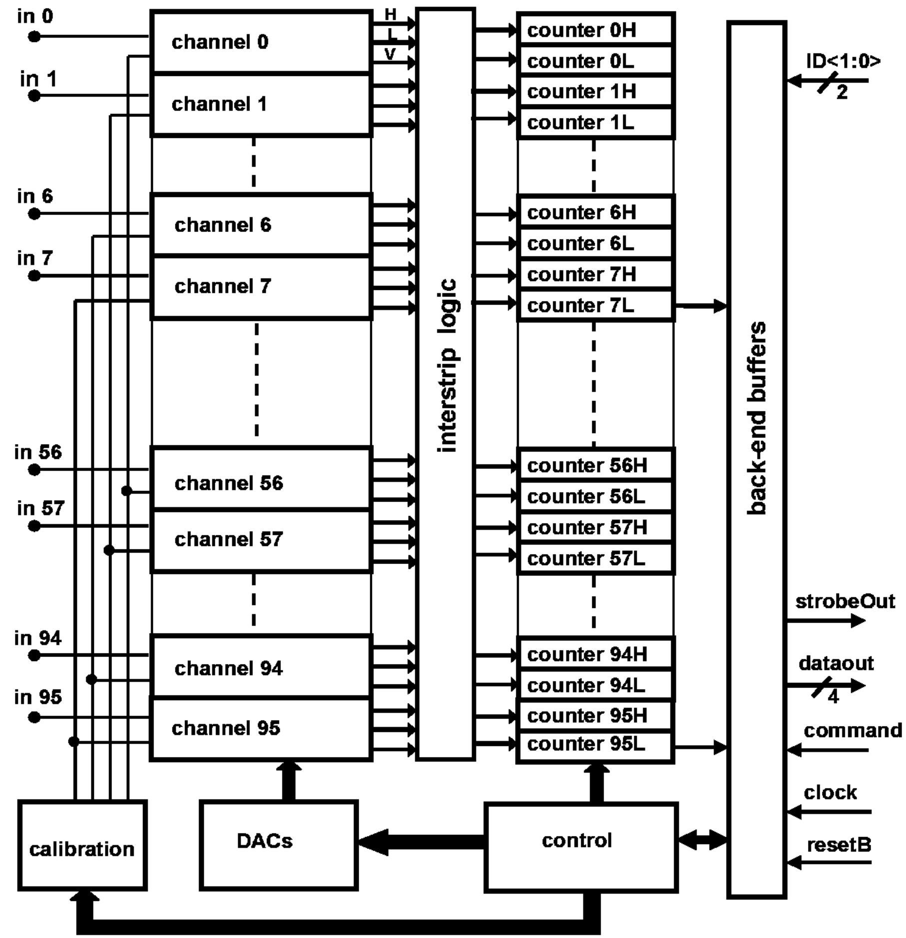
Readout ASIC design

Front-end channel



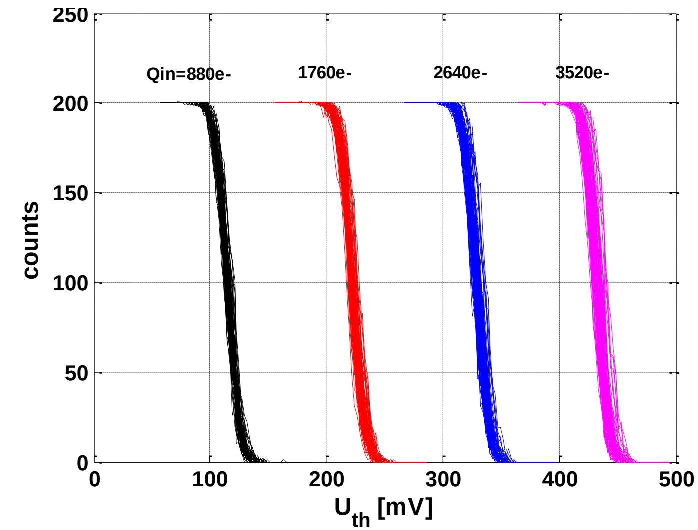
Signal for the interstrip logic
Threshold to be set just above the noise;
any coherent noise would kill the idea

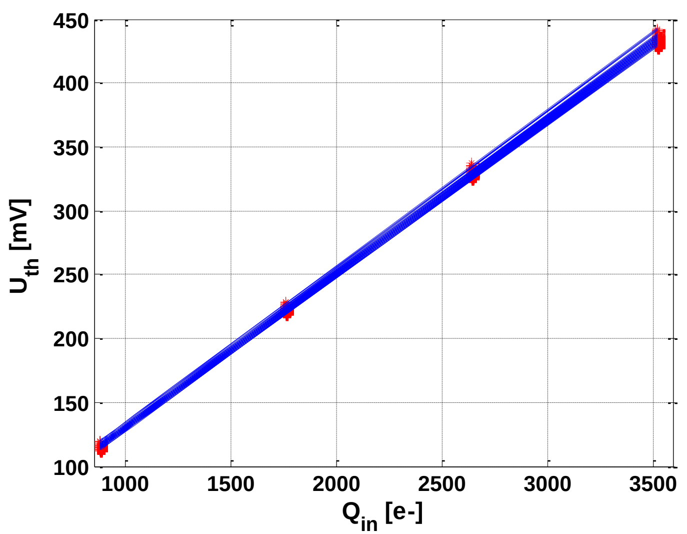
96-channel ASIC



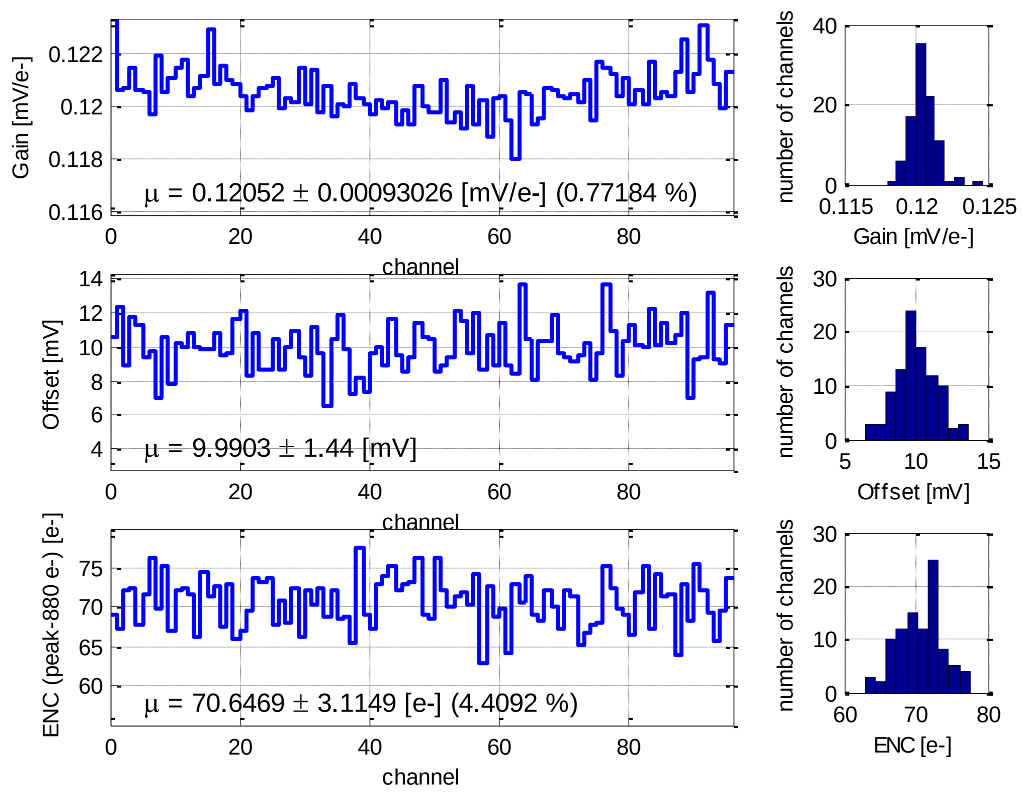
ASIC performance I

Measurement method

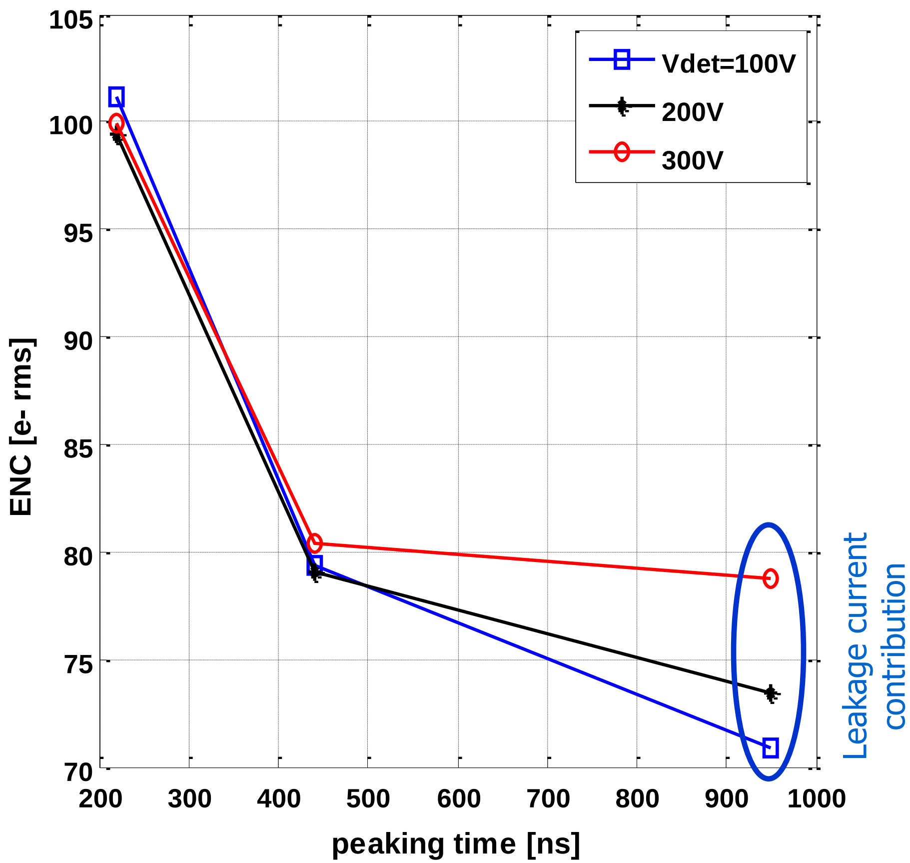


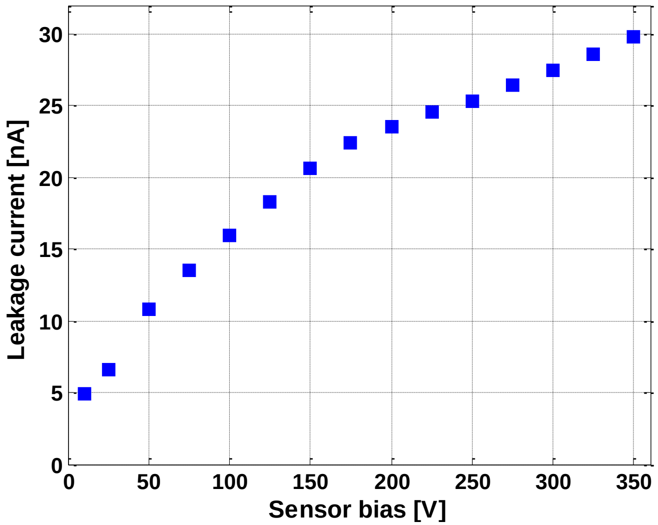


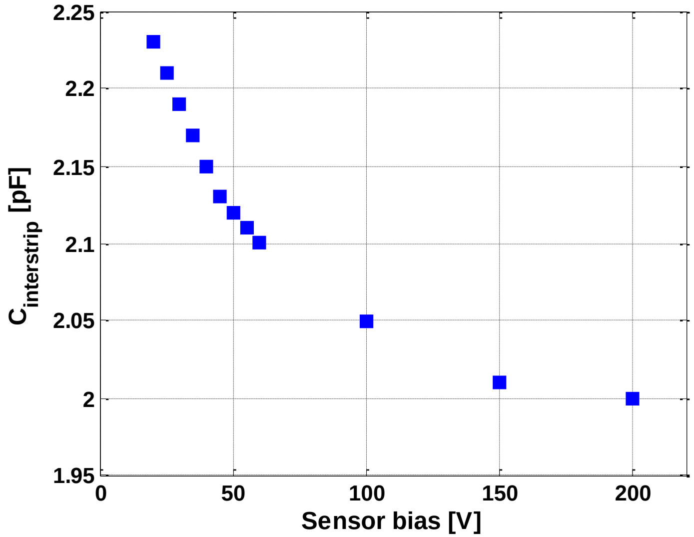
Parameters extracted for each channel:
(gain, offset, ENC)
ASIC connected to the detector (C_t ~3 pF)
Electronic test pulses



ENC vs shaping and detector bias
(from electronic calibration test)



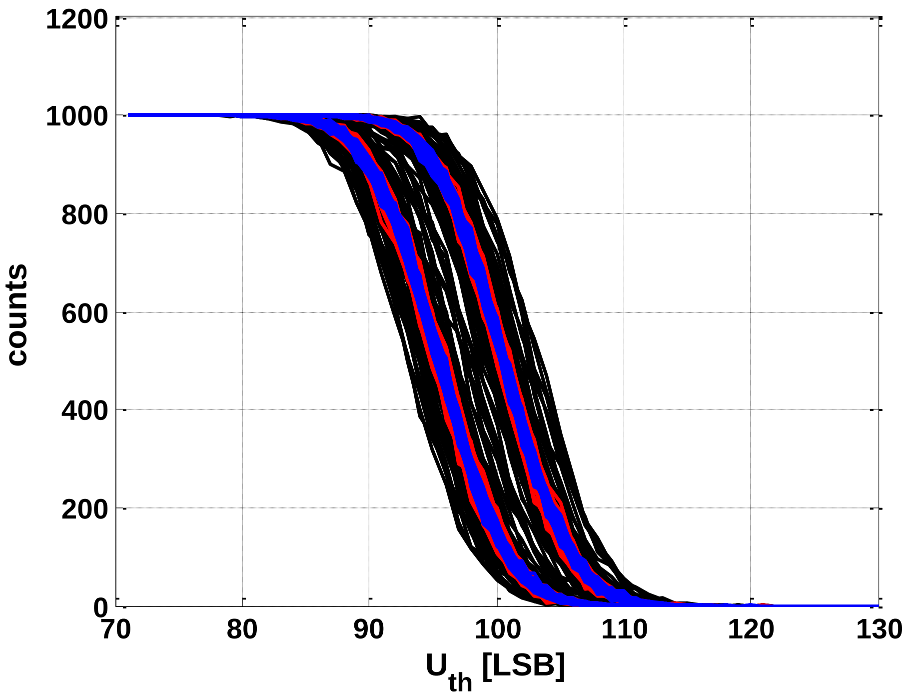


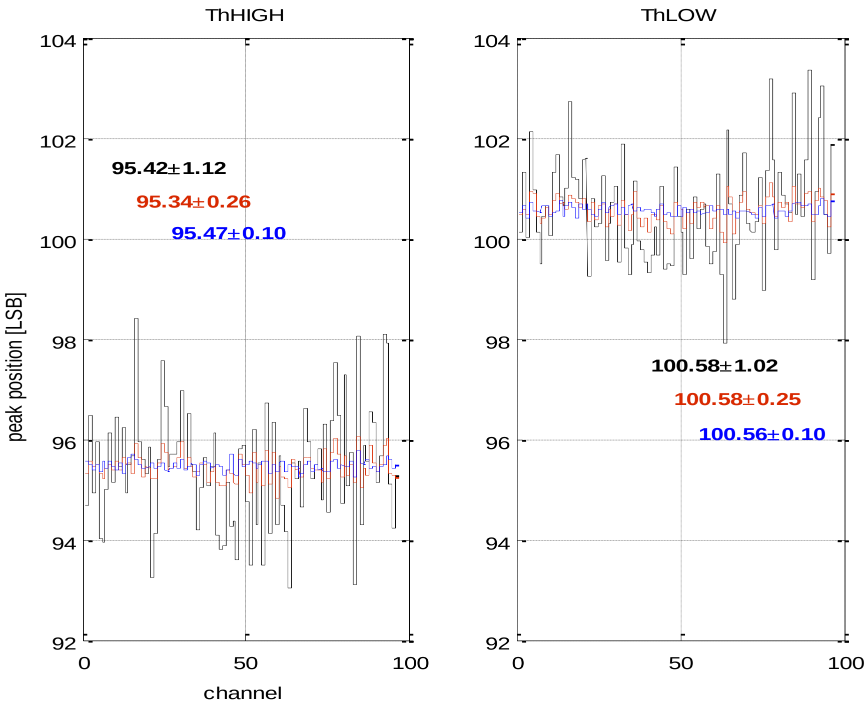


Trimming of the discriminator thresholds

Threshold trimming on the channel basis is essential for the window mode operation

By an iterrative trimming procedure matching at the level of 0.1 LSB rms of the threshold is achieved (2 e^- rms input equivalent)





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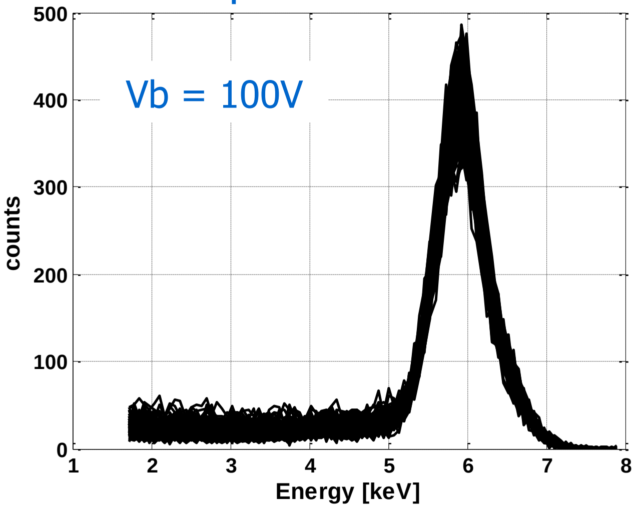
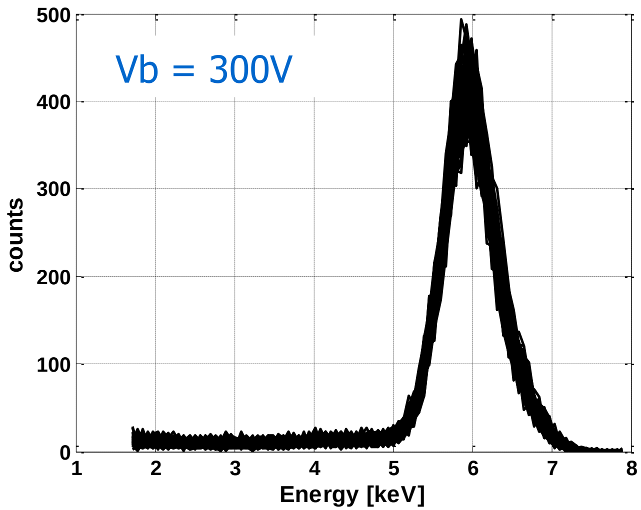
Fe-55 spectrum (192 strips)

5.9 keV + 6.4 keV (16%)

Higher bias voltage reduces charge sharing

Strip side irradiation

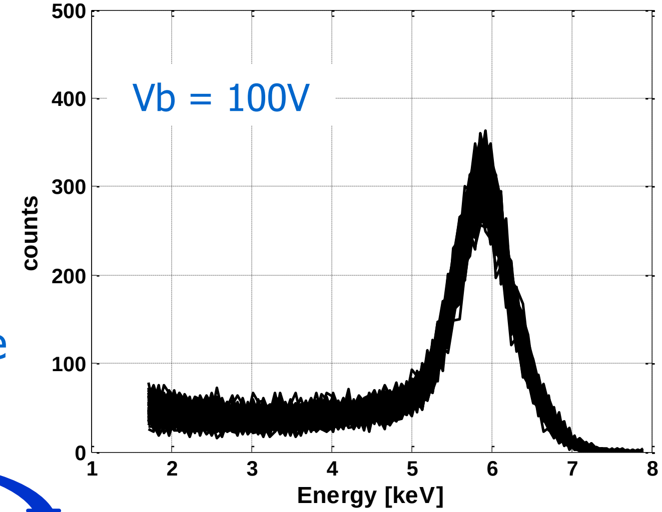


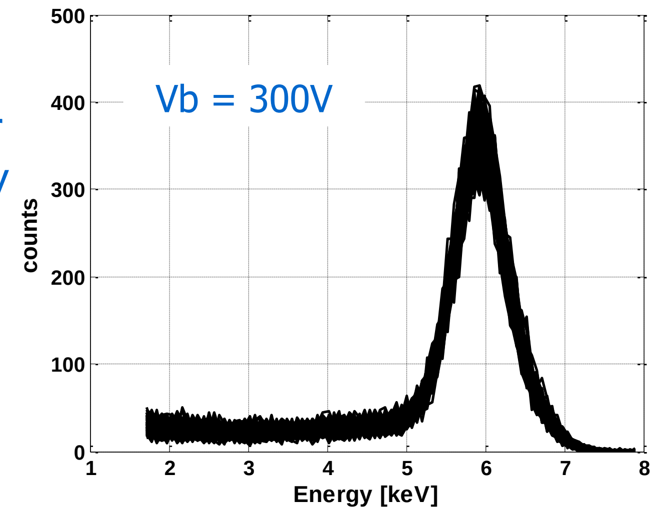


Some advantage of strip side irradiation

Difference reduced for higher X-ray energies

Ohmic side irradiation



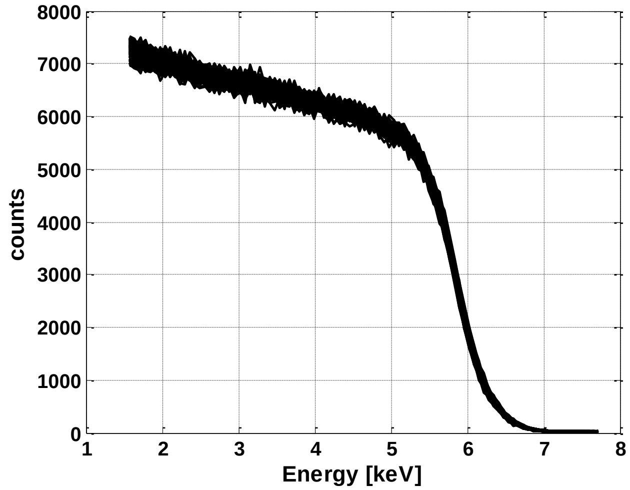


Effectiveness of the interstrip logic

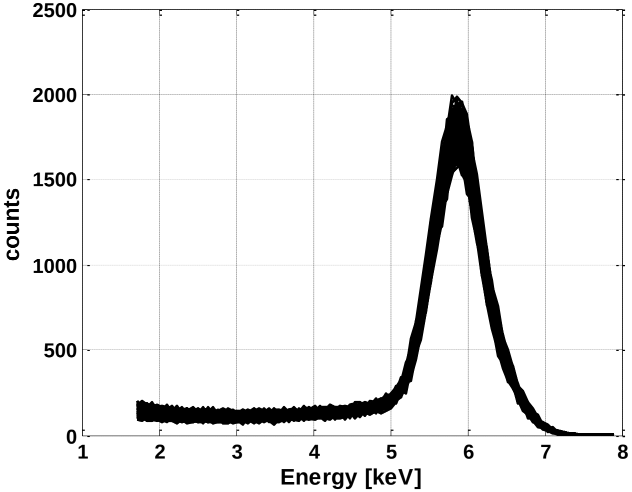
Fe-55 source: 5.9 keV + 6.4 keV

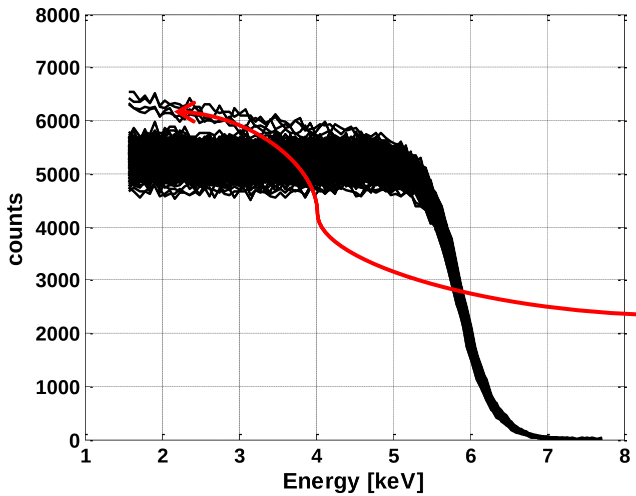
Threshold scan (192 strips)

Window scan (192 strips)



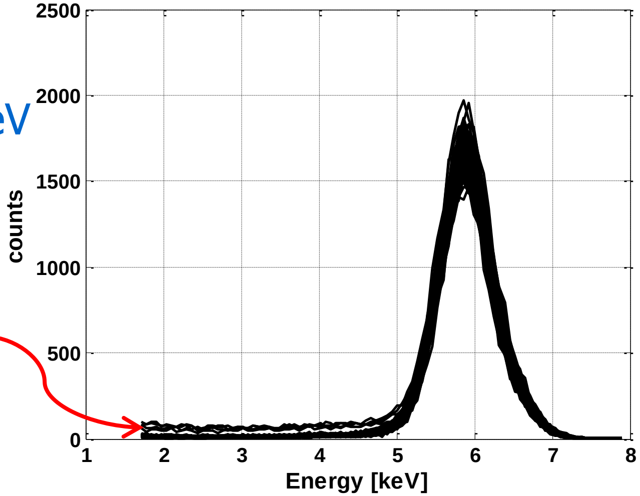
Interstrip logic not used



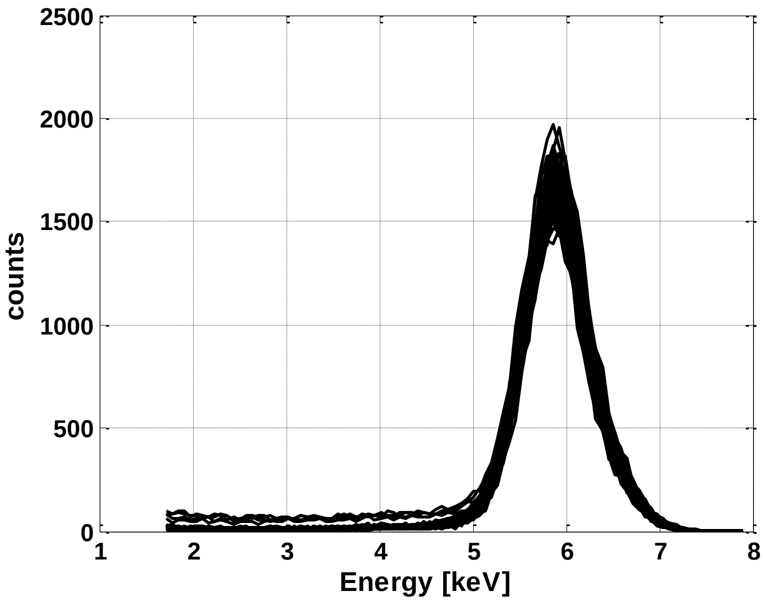


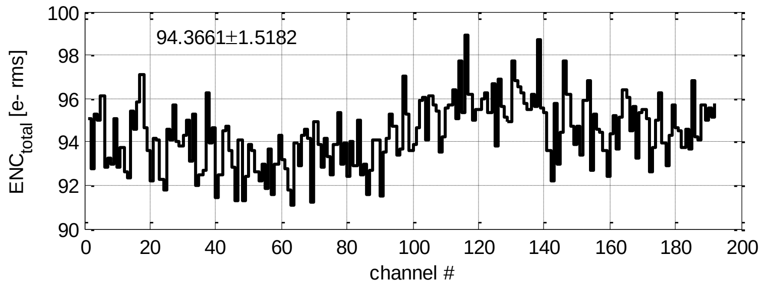
Interstrip logic used
Veto threshold: 0.8 keV

4 edge channels with no neighbours on one side



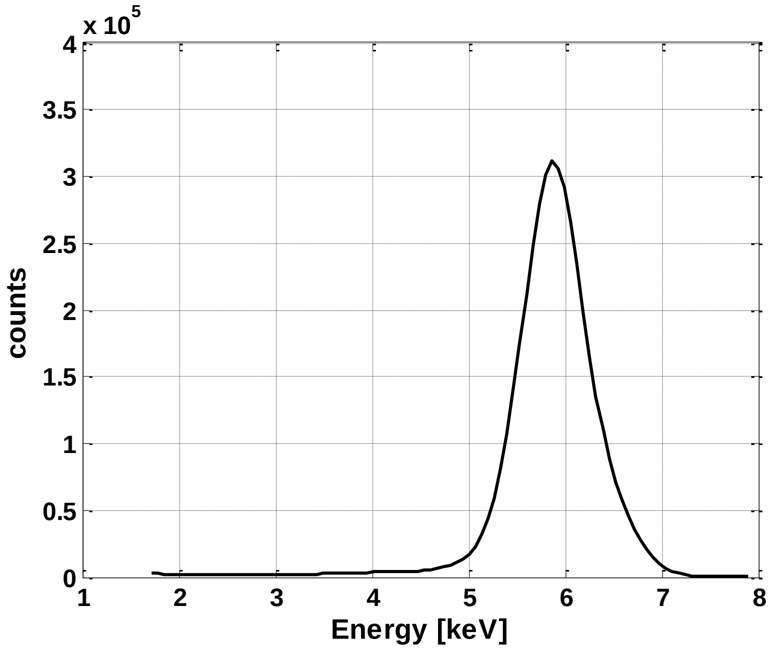
Energy resolution – uniformity
Fe-55 source: 5.9 keV + 6.4 keV





Average for 192 strips (2 ASICs)
ENC = 94.37 e^- rms, ΔE = 812 eV FWHM

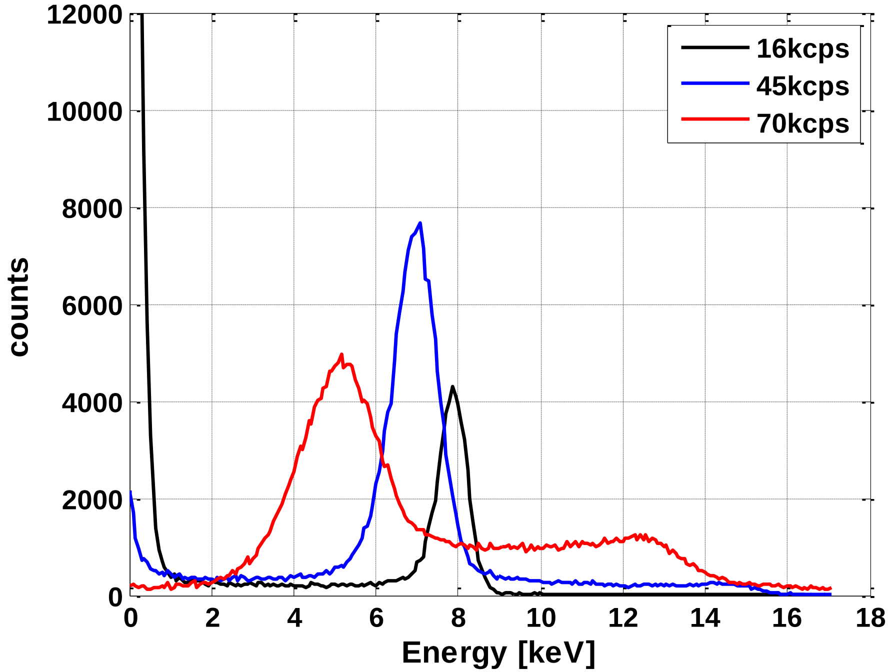
Summed spectrum
ENC = 94.45 e^- rms; ΔE = 812 eV FWHM
Note broadening of the peak by 6.4 keV line



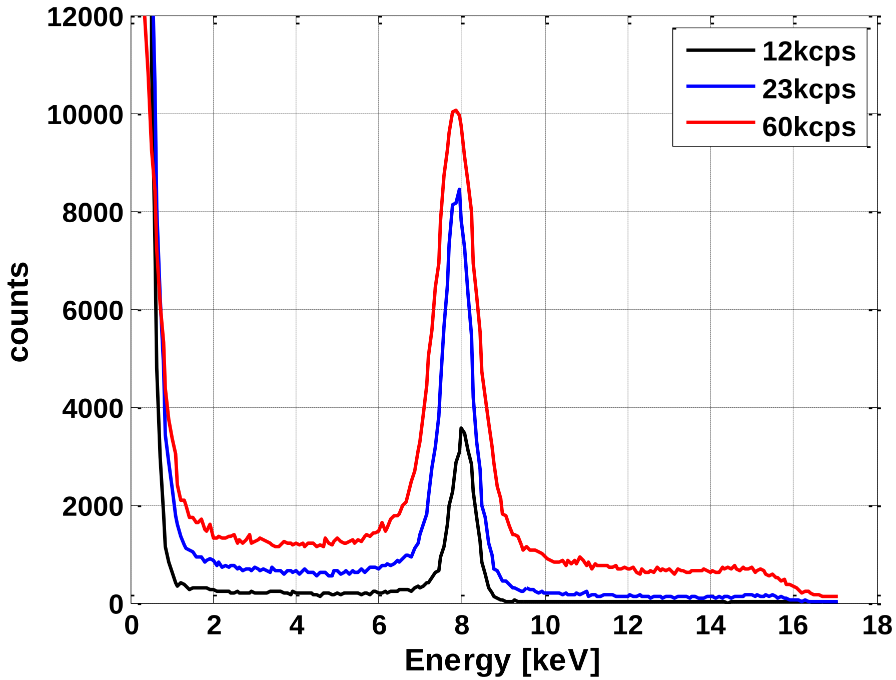
Energy resolution of the whole detector is as good as of single channel

Baseline stability

Baseline restorer OFF

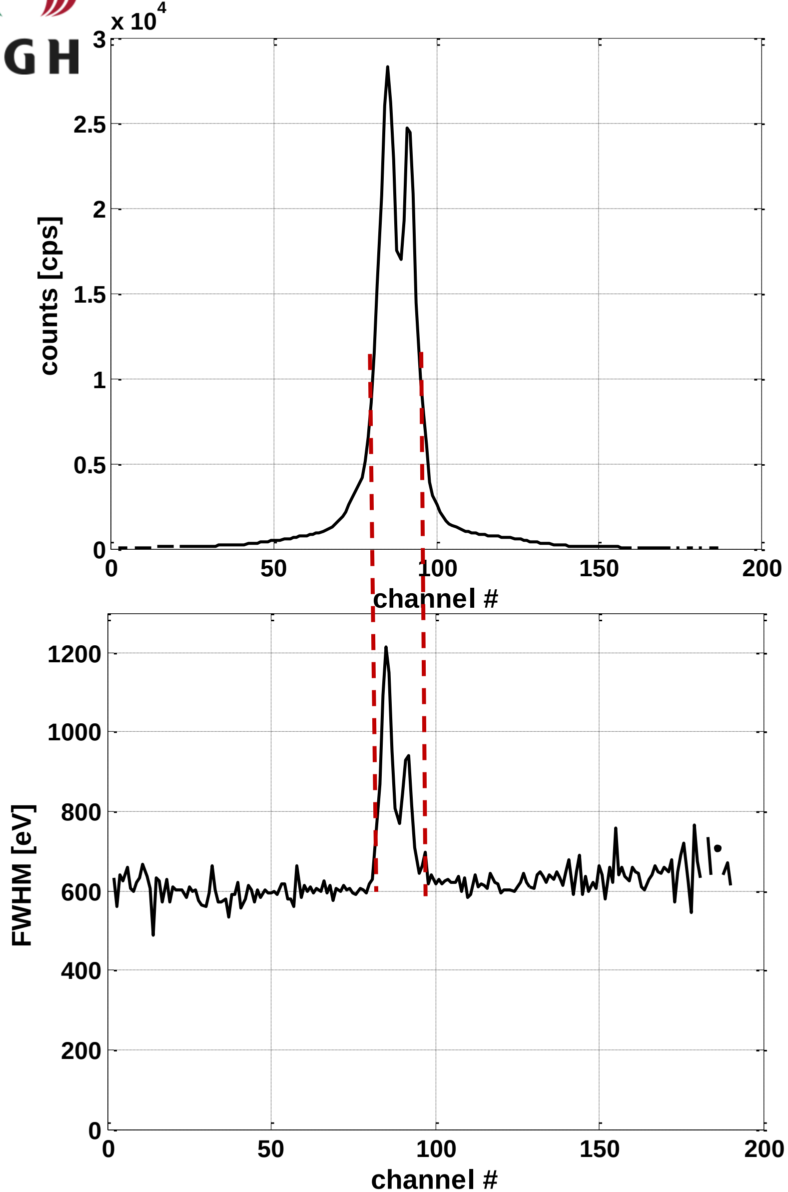


Baseline restorer ON

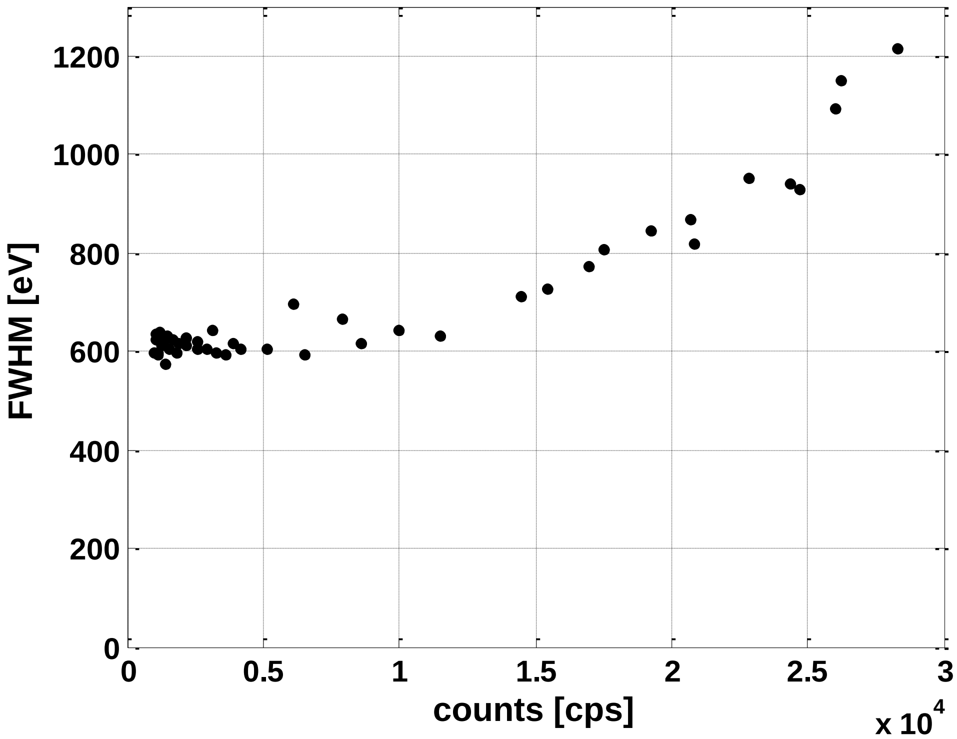


Baseline restorer is essential for fine energy discrimination

Detector performance II



Energy resolution vs count rate
Cu-Kα radiation : 8.04 keV
Interstrip logic used



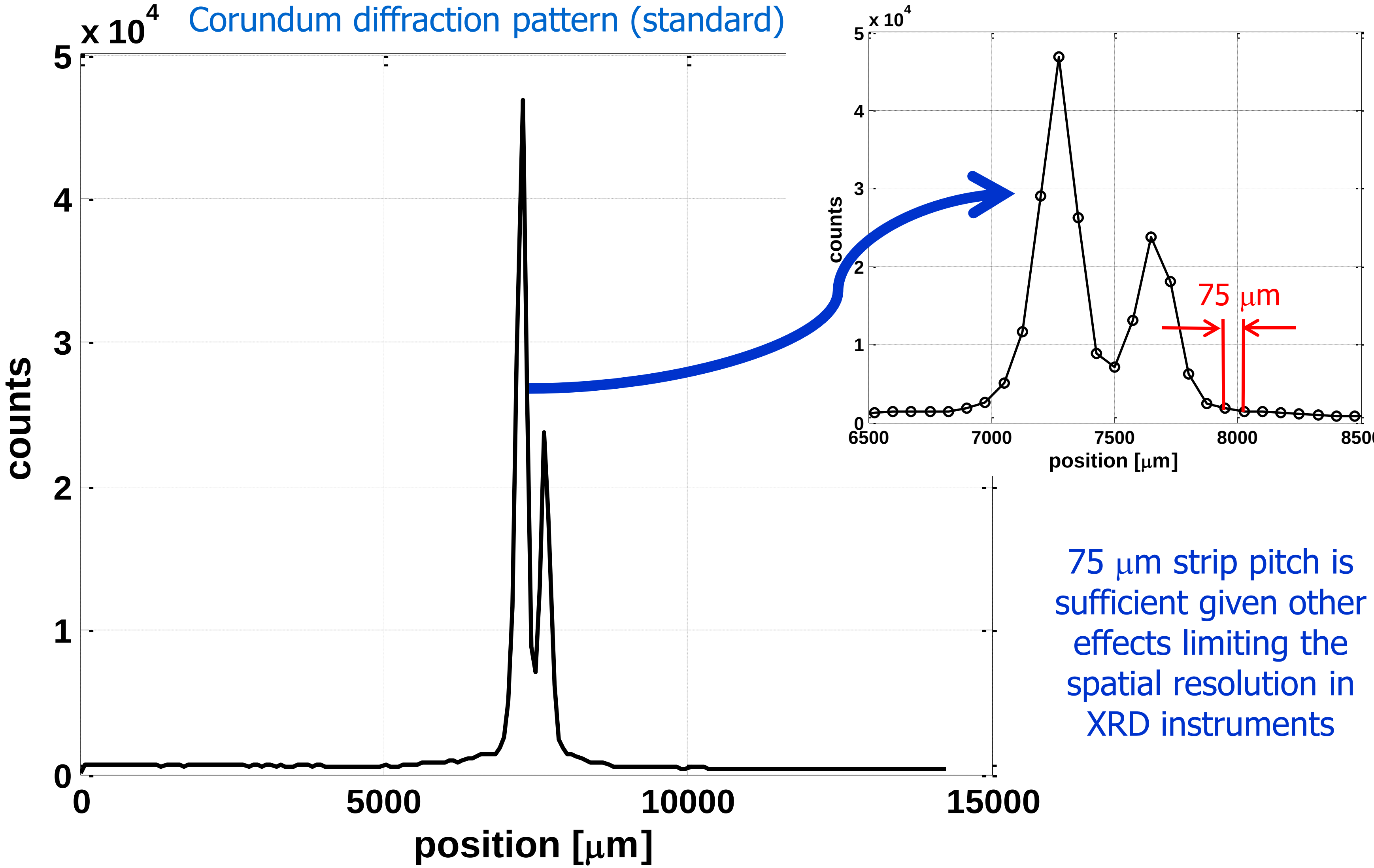
electronic noise limit

600 eV FWHM ⇔ 70 e^- rms

Detector performance III

Spatial resolution

Corundum diffraction pattern (standard)

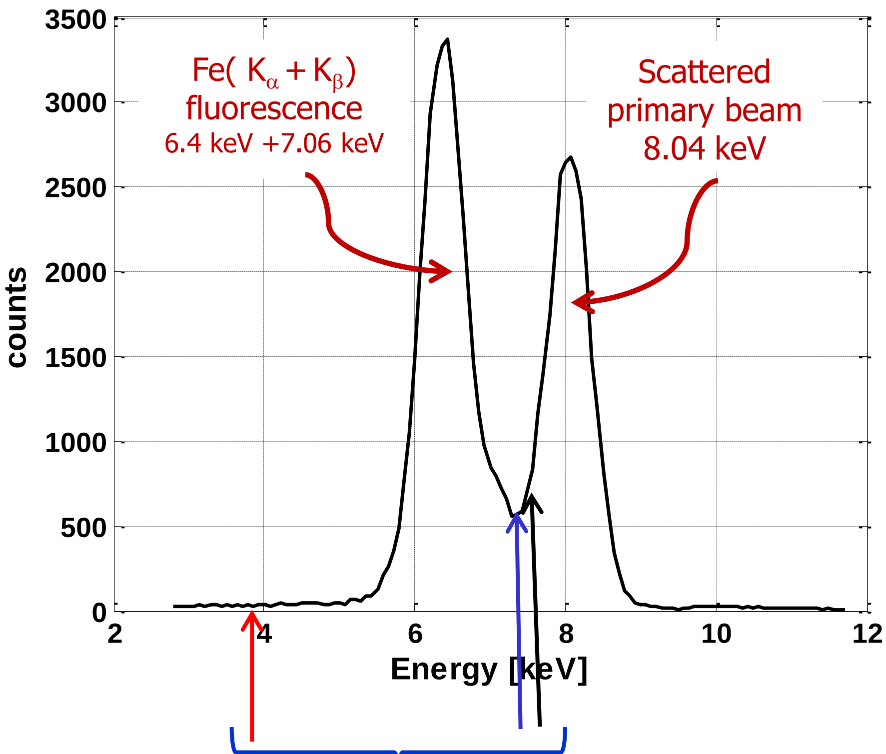


75 µm strip pitch is sufficient given other effects limiting the spatial resolution in XRD instruments

Detector performance IV

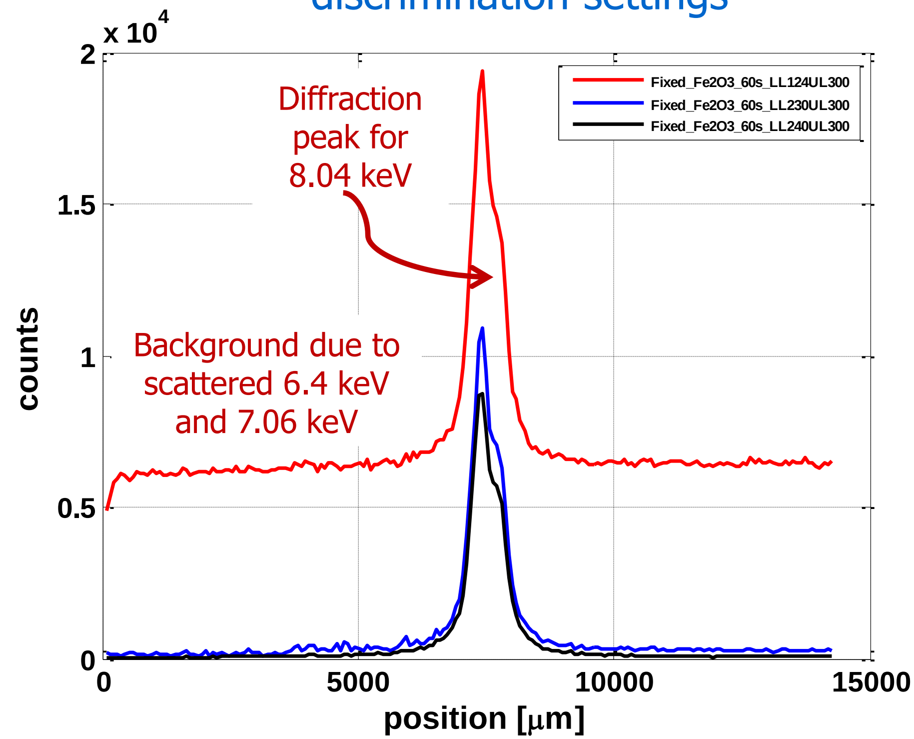
Fe fluorescence suppression

Energy spectrum of a Fe_2O_3 sample



Low discrimination threshold

Diffraction pattern for different discrimination settings



Low threshold = 3.2 keV, no interstrip logic: Peak/BG = 3.1
Low threshold = 7.4 keV, no interstrip logic: Peak/BG = 72
Low threshold = 7.7 keV, interstrip logic: Peak/BG = 108

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Summary

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- Silicon strip detector technology has been proved to be suitable for X-ray detectors for 1-D diffraction
- Energy resolution at below 800 eV FWHM at room temperature, which is sufficient for electronic discrimination of Fe fluorescence (when using a Cu anode tube) has been demonstrated
- Implementation of the interstrip logic allows suppressing the charge sharing effects with negligible effect on detection efficiency
- Uniformity of gain and discrimination thresholds is essential; input equivalent channel-to-channel spread should be negligible compared to ENC
- Optional fast shaping makes the detector suitable for high count rate applications (up to 7×10^5 cps) at expence of slightly worse energy resolution