Influence of Backscattering on the Spatial Resolution of Semiconductor X-ray Detectors

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Outline

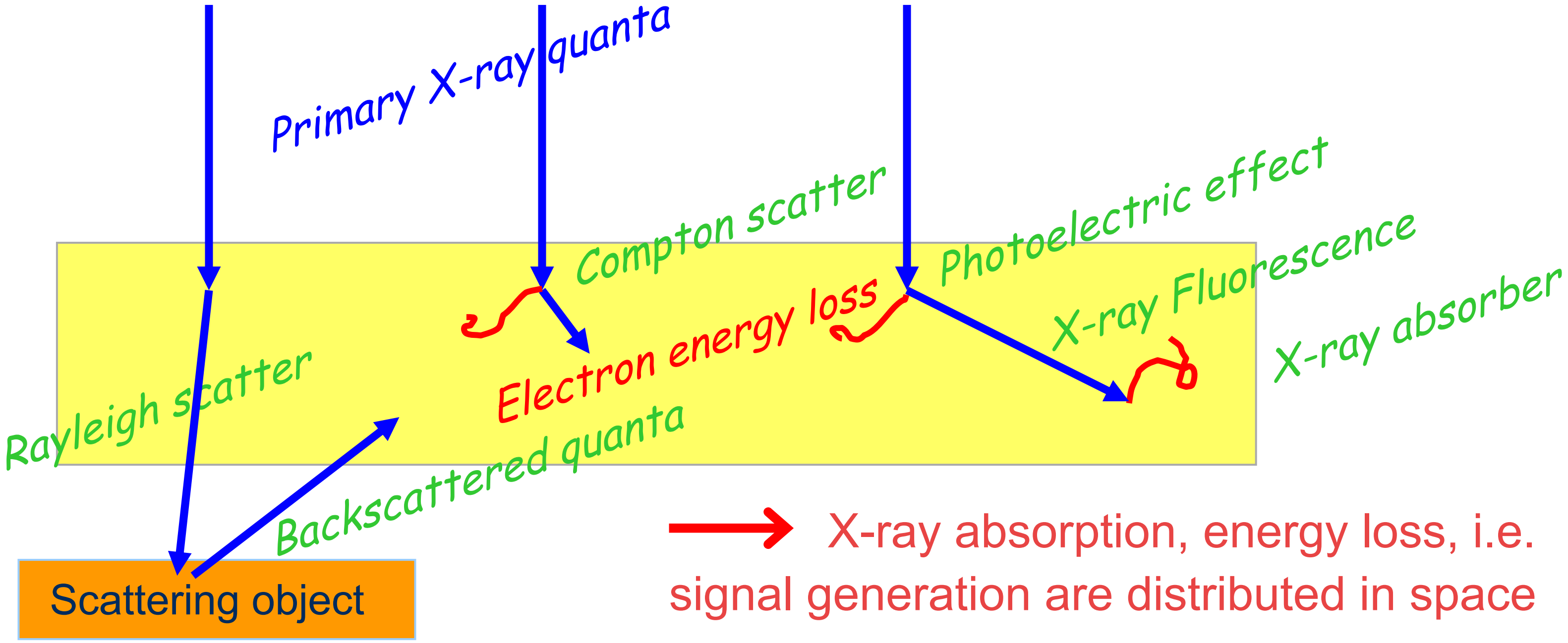
- Introduction
- What limits spatial resolution?
- Simulations with and without backscattering objects
- Results
- Summary and conclusions

Introduction

- Medical X-ray detectors
  - Past: film/screen combination, image intensifier, storage phosphor
  - Future: semiconductor-based flat-panel detector
- Registration concepts
  - Scintillator + matrix of photodiodes and switches
  - Directly absorbing semiconductor + matrix of switches
  - Signal integration or counting of X-ray quanta
- Spatial resolution required
  - Soft tissue: 0 … 2 lp/mm (line pairs per mm)
  - Bones: 0 … > 3 lp/mm
  - Dental, mammography: 0 … > 5 lp/mm … 10 lp/mm … 20 lp/mm

What limits spatial resolution?

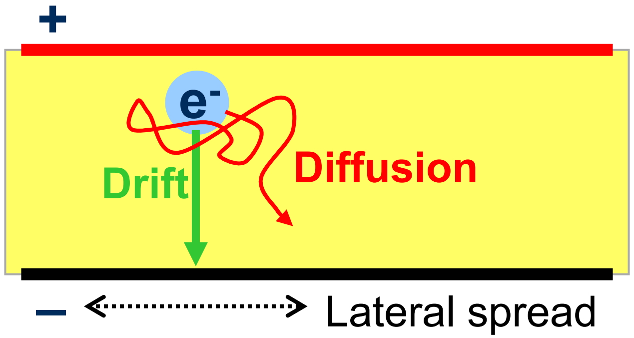
- X-ray interaction with absorber
  - Elastic (Rayleigh) scattering
  - Inelastic (Compton) scattering generating fast electrons
  - Photoelectric absorption generating fluorescent quanta and fast electrons
- Electron energy loss
  - Elastic scattering
  - Multiple excitation of electron-hole pairs



→ X-ray absorption, energy loss, i.e. signal generation are distributed in space

What else limits spatial resolution?

- Transport (for directly absorbing detectors)
  - Charge carriers are collected by drift
  - Charge carriers are spread by diffusion



Simple model:

Transit time $t_{tr} = \frac{d^2}{\mu U}$

Diffusion constant $D_{diff} = \frac{\mu k T}{e}$

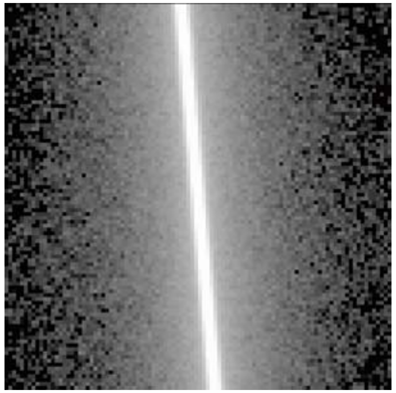
Diffusion length $L_{diff} = \sqrt{D_{diff} t_{tr}} = \sqrt{\frac{kTd^2}{eU}}$

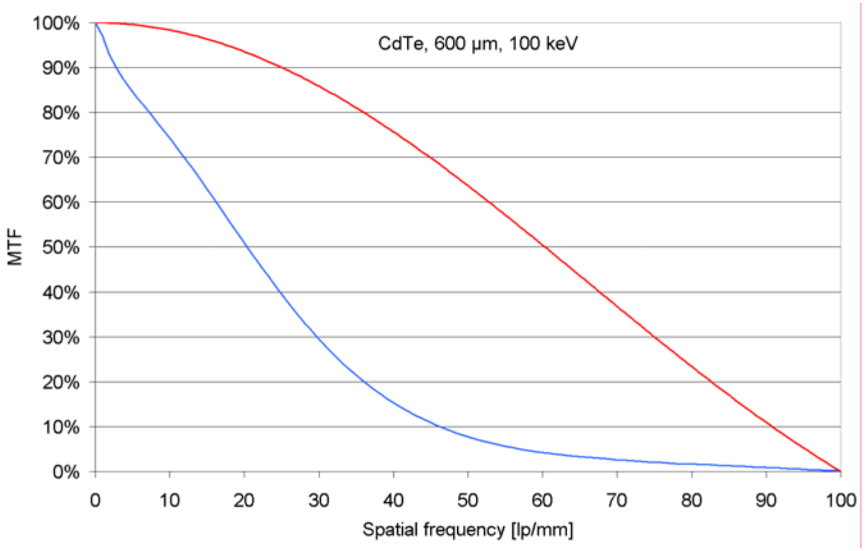
independent of material properties!

- Integration and sampling
  - Signal is integrated over pixel area
  - Ambiguity by sampling for spatial frequencies > Nyquist frequency

Simulations

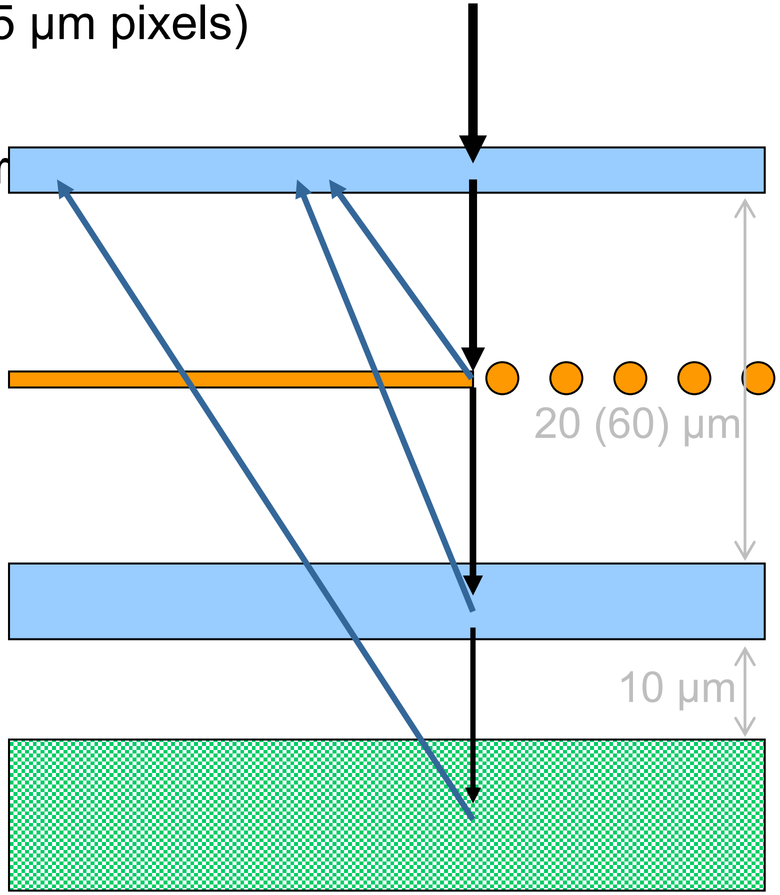
- Monte Carlo simulation
  - Program, ROSI (Roentgen Simulation), based on EGS4 algorithm
  - Mono-energetic range 20 keV … 120 keV
  - Common spectra 28 kV … 120 kV
- X-ray fan beam hits a pixelated detector grid
  - Slightly (5°) tilted to produce oversampling
- Line spread function
  - Used to calculate the modulation transfer function (MTF)





Setup (1)

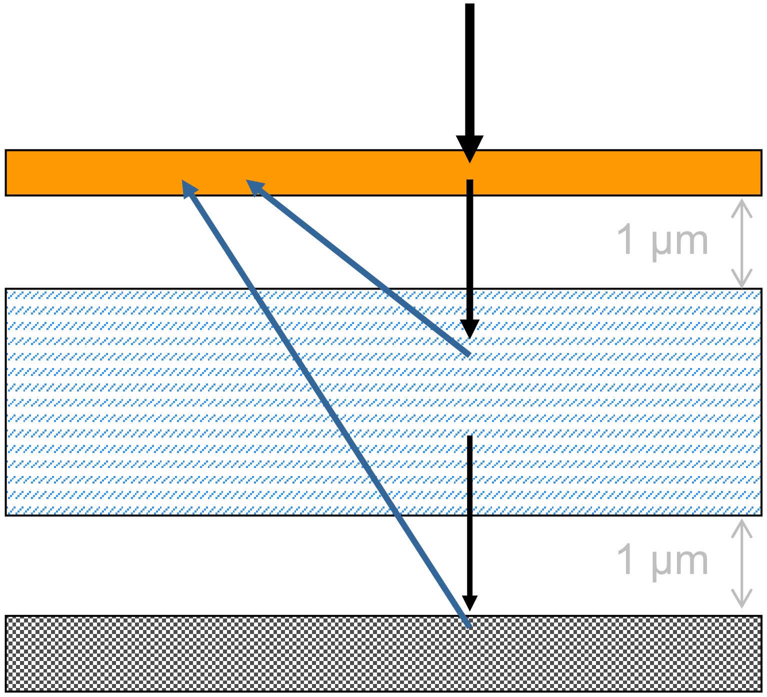
- Materials and detectors investigated
  - 300 µm and 700 µm Si on Medipix-2 (55 µm pixels)
  - 300 µm GaAs on Medipix-2 (55 µm pixels)
- Setup
  - Absorbing semiconductor layer
    300/700 µm Si (300 µm GaAs)
  - Bump-bond level
    1.8 µm In layer
    (bumps 21.8 µm in diameter)
  - Medipix-2 chip
    500 µm Si
  - Printed circuit board
    1 mm PMMA



Setup (2)

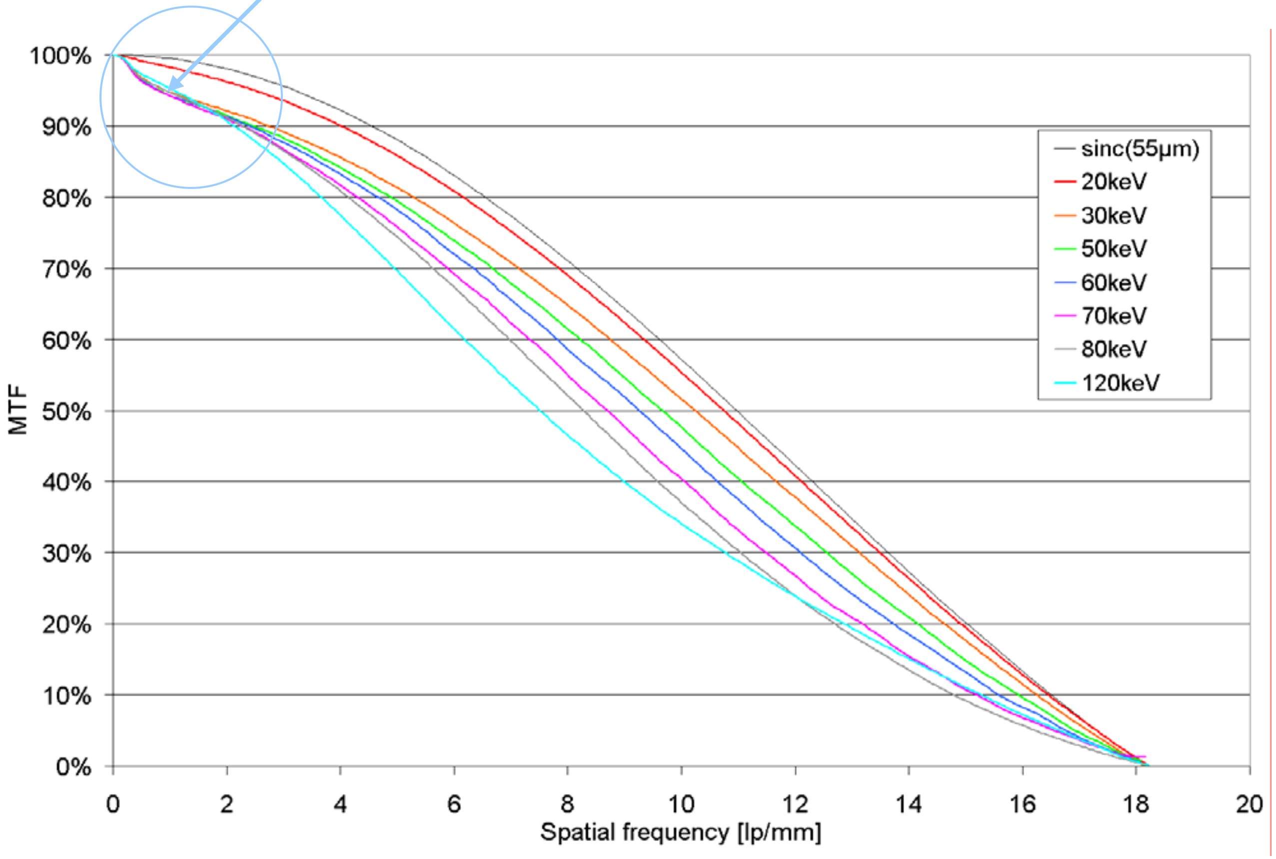
- Materials and detectors investigated
  - 200 µm Se on a-Si readout matrix (70 µm pixels)
  - 420 µm CsI on a-Si readout matrix (143 µm pixels)

- Setup
  - Absorbing layer 200 µm Se (420 µm CsI)
  - Glass substrate 3 mm Corning 7059
  - Protective shield 1 mm Pb



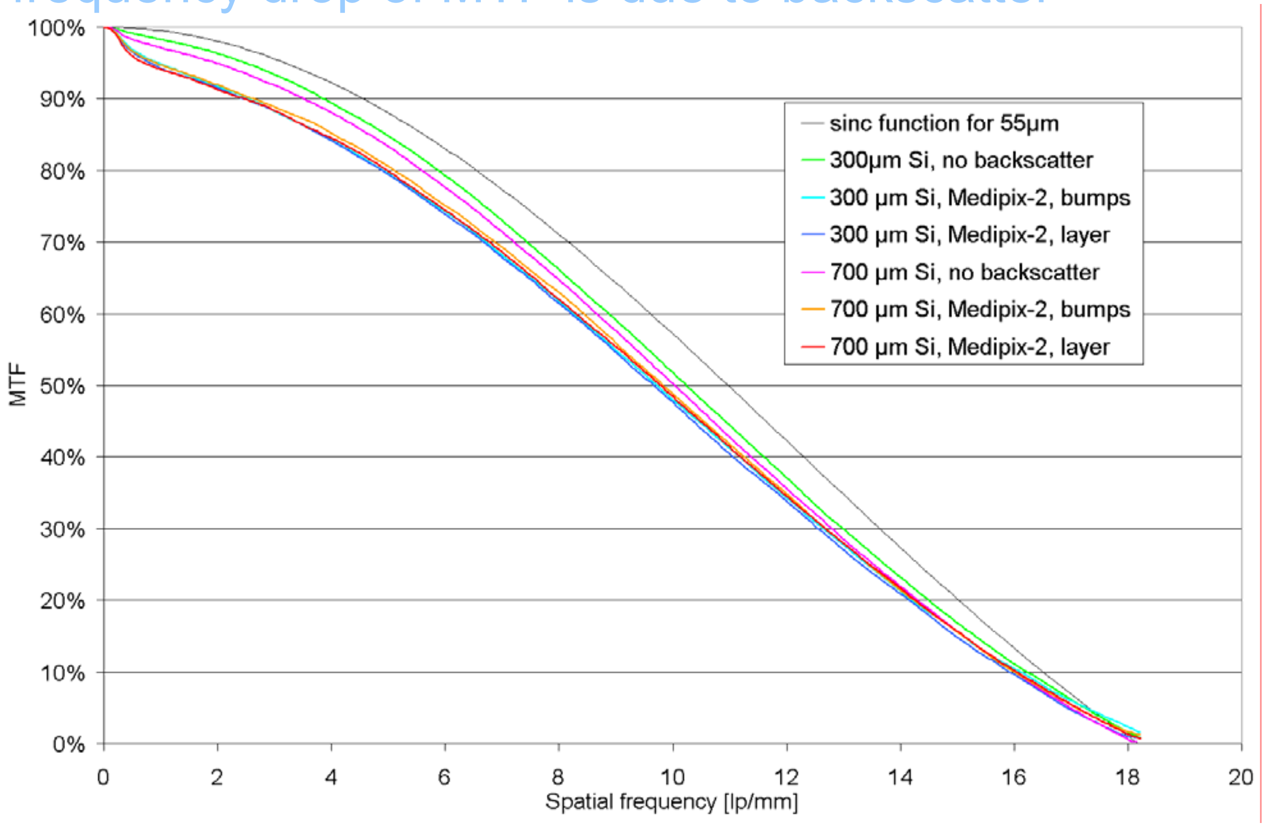
Results (1)

- 20 keV ... 120 keV
- 300 µm Si with Medipix-2 and chip board
- Low-frequency drop visible for E > $E_K(\text{In})$ = 27.94 keV



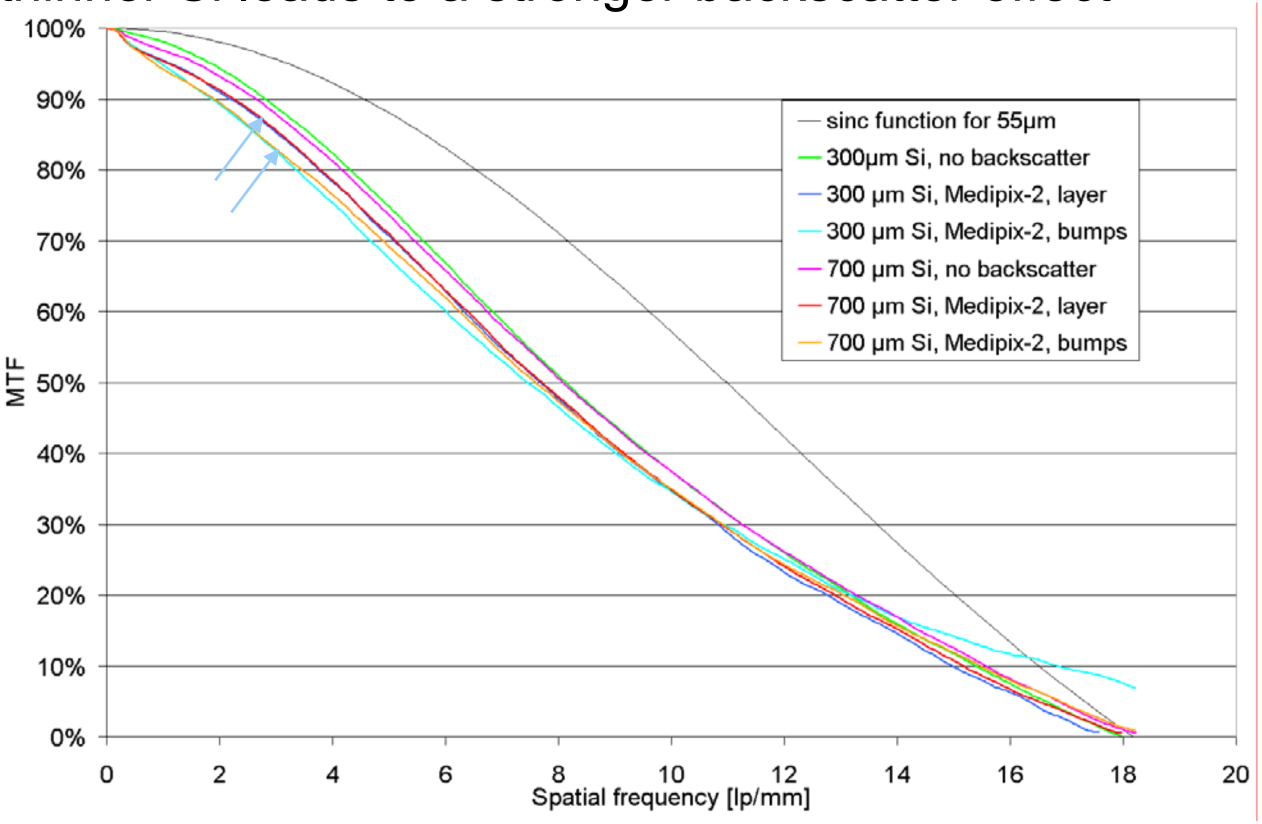
Results (2)

- 300 / 700 µm Si with Medipix-2 and chip board at 50 keV
- Si without backscattering objects behind the absorber
- In bumps or homogeneous layer
- Low-frequency drop of MTF is due to backscatter



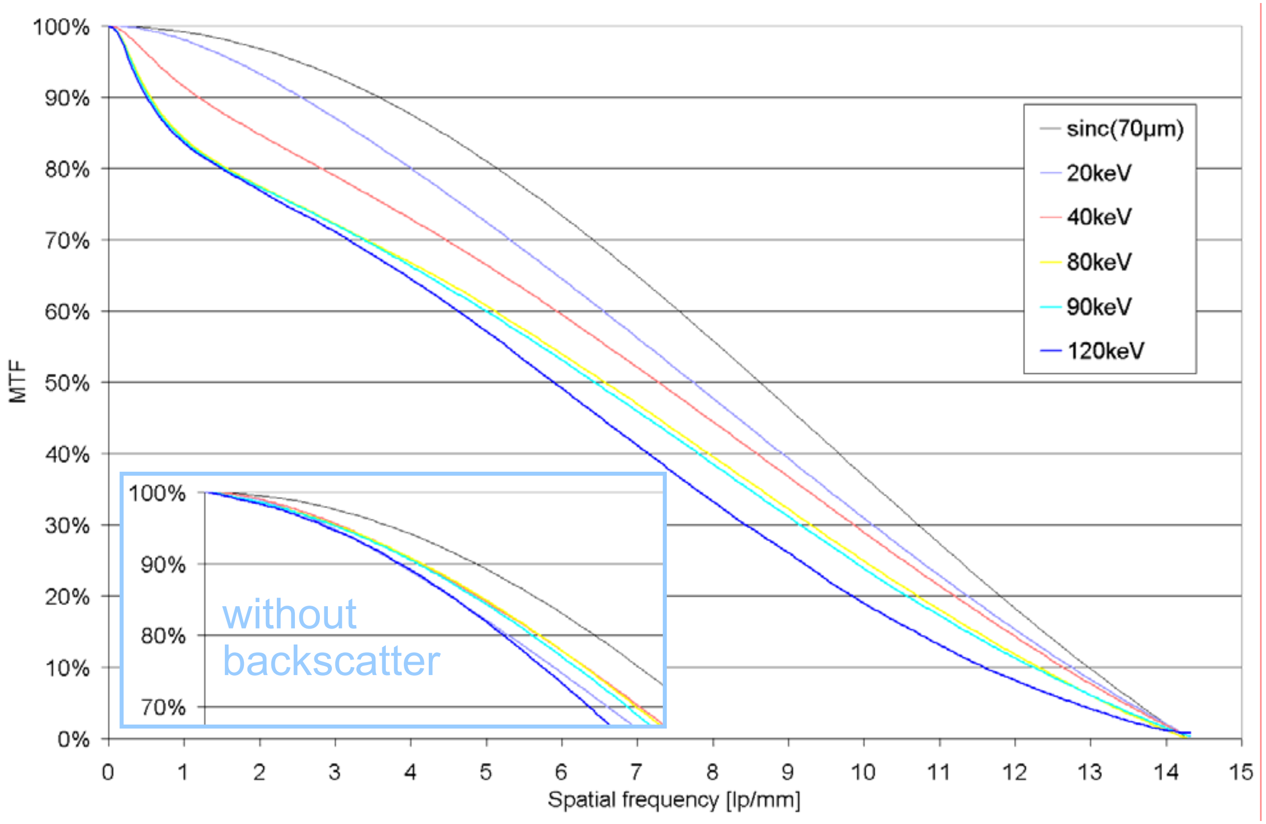
Results (3)

- 300 / 700 µm Si with Medipix-2 and chip board at 120 keV
- Backscattered quanta from chip and chipboard are partly absorbed by the In layer, but penetrate the gaps between the bumps
- The thinner Si leads to a stronger backscatter effect



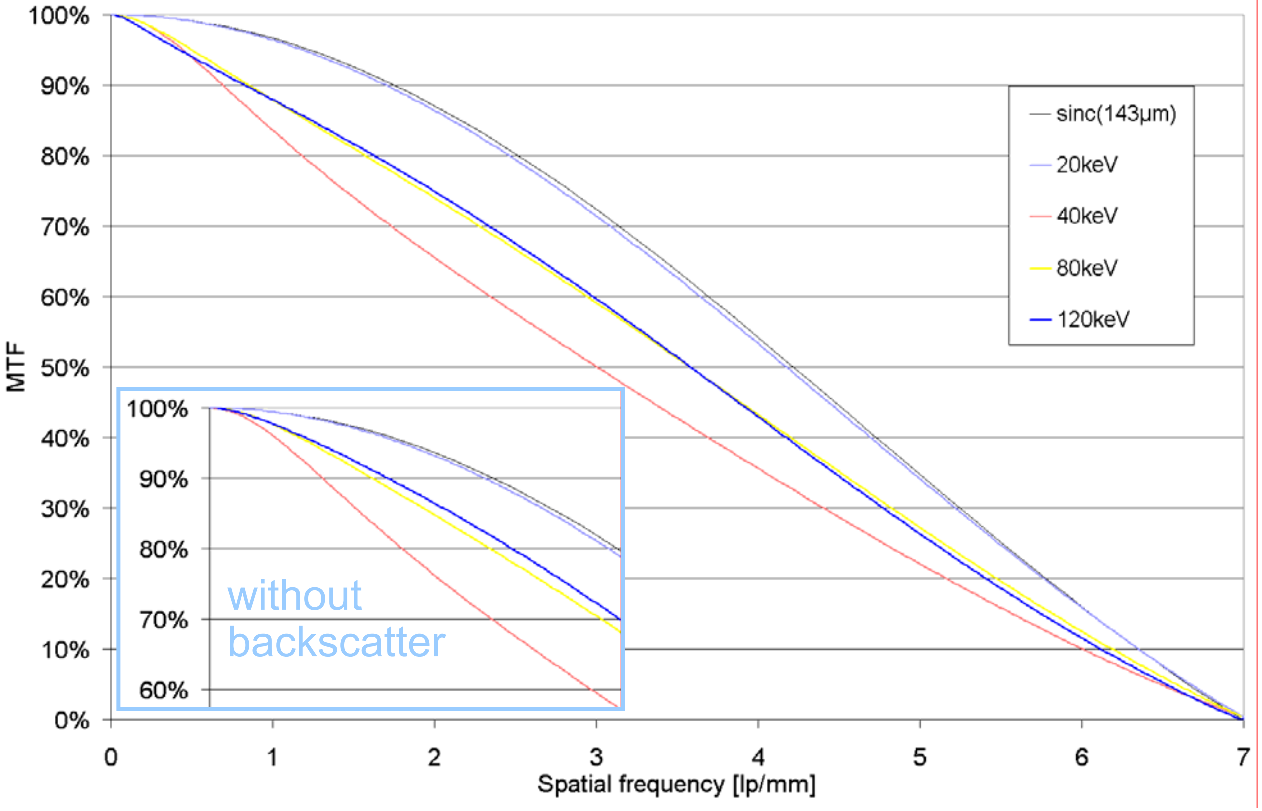
Results (4)

- 200 µm Se layer with a-Si readout matrix on glass substrate (3 mm Corning 7059) and additional 1 mm Pb shielding
- Low-frequency drop caused by backscatter (compare to inset)



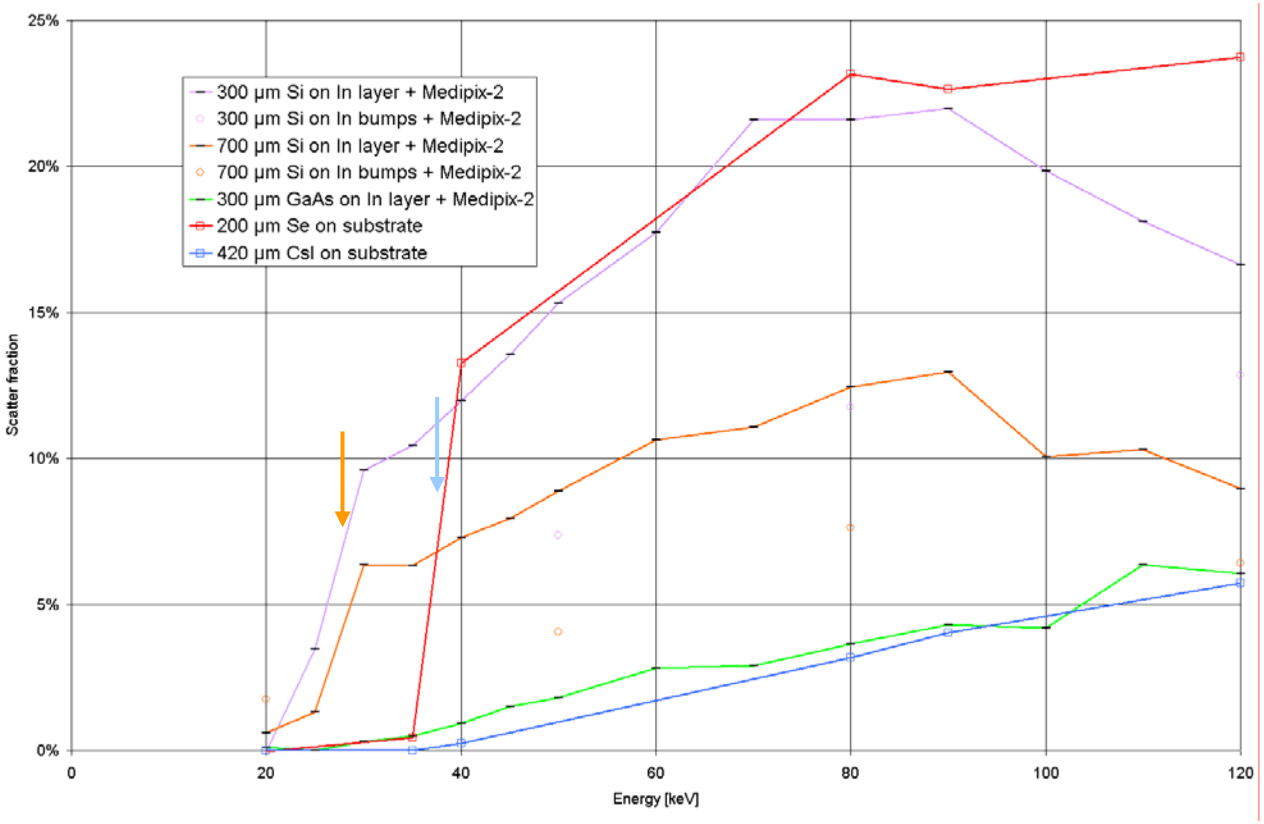
Results (5)

- 420 µm CsI layer with a-Si readout matrix on glass substrate (3 mm Corning 7059) and additional 1 mm Pb shielding (optical effects on MTF not taken into account)
- Low backscattering has low effect on MTF (compare to inset)



Scatter fraction

- Scatter fraction rises above K-edge of backscattering object
  - Indium bumps for Medipix-2, i.e. E > E_K(In) = 27.94 keV
  - Glass substrate for CsI and Se detectors, i.e. E > E_K(Ba) = 37.44 keV



Summary

- Upper limit for MTF is the sinc function of the pixel size
  - At energies below K-edge, the MTF is close to the sinc function
  - At energies above K-edge, fluorescence spreads the signal, thus reducing resolution
  - Above 50 keV, resolution is reduced by the range of fast electrons
  - Carrier transport has an influence on MTF
- Transmitted and backscattered quanta reach the whole detector
  - MTF is reduced at low spatial frequency → low-frequency drop
  - Effect increases above K-edge of backscattering object
- Monochromatic quanta and common X-ray spectra lead to comparable results

Conclusions

- The effect of backscatter on spatial resolution must not be ignored
    - Important with thin absorbers, where a high fraction of incident quanta is transmitted
    - Dependent on materials behind absorber (substrate, chips)
- Interpretation of charge sharing may be wrong due to backscattered quanta
    - Can be tested by experiments below/above K-edge

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