Characterization of 3D thermal neutron semiconductor detectors

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This work has been done within the 3D-RID project and the Medipix collaboration.

Outline

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- Motivation – why neutron detectors?
- Neutron detection principle
- Planar silicon neutron detectors
- 3D detectors – simulations
- 3D detectors – measurements
- Conclusions and further outlook

Motivation – neutron radiography

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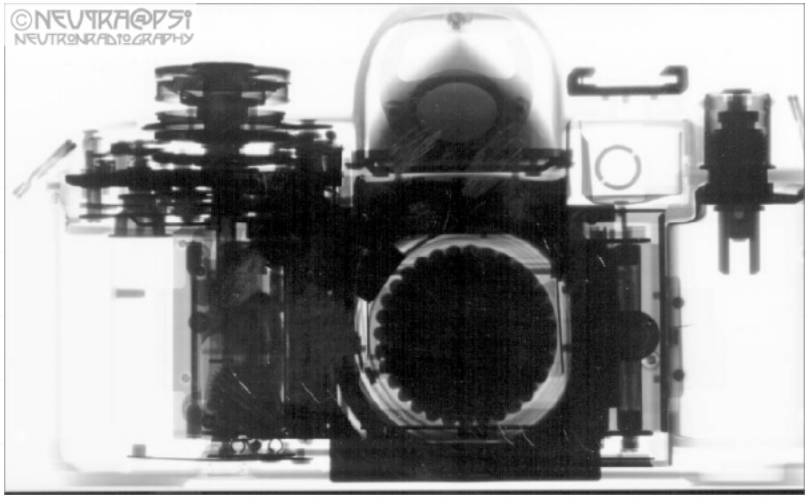
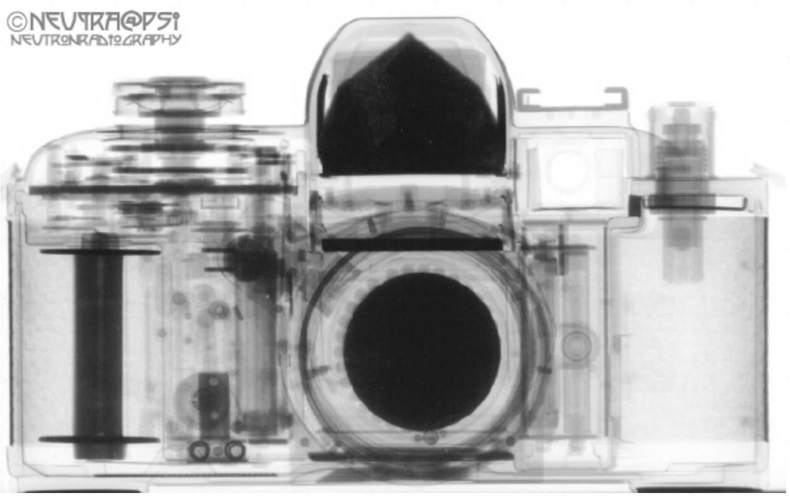
- While X-rays are attenuated more effectively by heavier materials like metals, neutrons allow to image some light materials such as hydrogenous substances with high contrast.
- Neutron radiography can serve as complementary technique to X-ray radiography



X-rays



Neutrons

In the X-ray image, the metal parts of the photo camera are seen clearly, while the neutron radiogram shows details of the plastic parts.

Medipix pixel device

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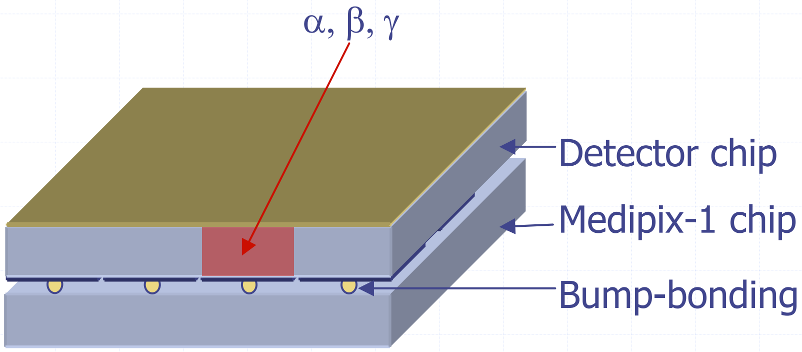
- Planar 300 μm thick silicon pixel detector (GaAs and CdTe also available)
- Bump-bonded to Medipix readout chip containing amplifier, discriminator and counter for each pixel.

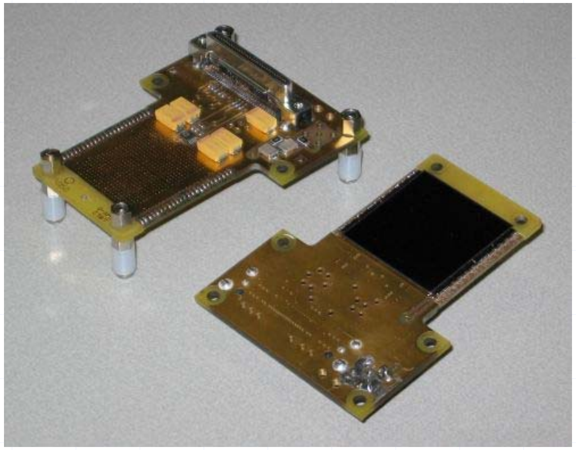


Medipix-2

Pixels: 256 x 256
Pixel size: 55 x 55 μm^2
Area: 1.5 x 1.5 cm^2

Medipix-2 Quad

Pixels: 512 x 512
Pixel size: 55 x 55 μm^2
Area: 3 x 3 cm^2



Adaptation of a silicon detector

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Silicon pixel detector can not detect neutrons directly.

$\Rightarrow$ Conversion of thermal neutrons to detectable radiation in a converter layer deposited on the detector surface.

Converter materials:

^{6}Li: ^{6}Li + n $\rightarrow$ α (2.05 MeV) + ^{3}H (2.72 MeV)

^{10}B: ^{10}B + n $\rightarrow$ α (1.47 MeV) + ^{7}Li (0.84 MeV) + γ (0.48MeV) (93.7%)

^{10}B + n $\rightarrow$ α (1.78 MeV) + ^{7}Li (1.01 MeV) (6.3%)

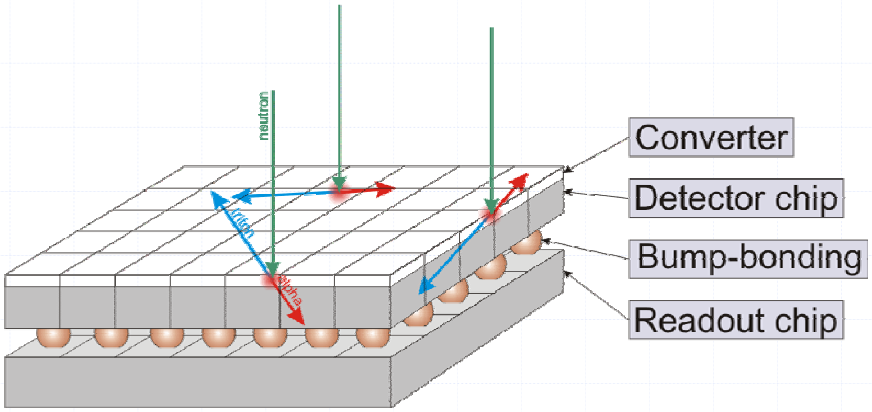
^{113}Cd: ^{113}Cd + n $\rightarrow$ ^{114}Cd + γ (0.56MeV) + *conversion electrons*

^{155}Gd: ^{155}Gd + n $\rightarrow$ ^{156}Gd + γ (0.09, 0.20, 0.30 MeV) + *conversion electrons*

^{157}Gd: ^{157}Gd + n $\rightarrow$ ^{158}Gd + γ (0.08, 0.18, 0.28 MeV) + *conversion electrons*

Detector:

300 μm thick silicon pixel detector (pixel size 55 μm) bump bonded to Medipix-2 readout chip.



Good spatial resolution

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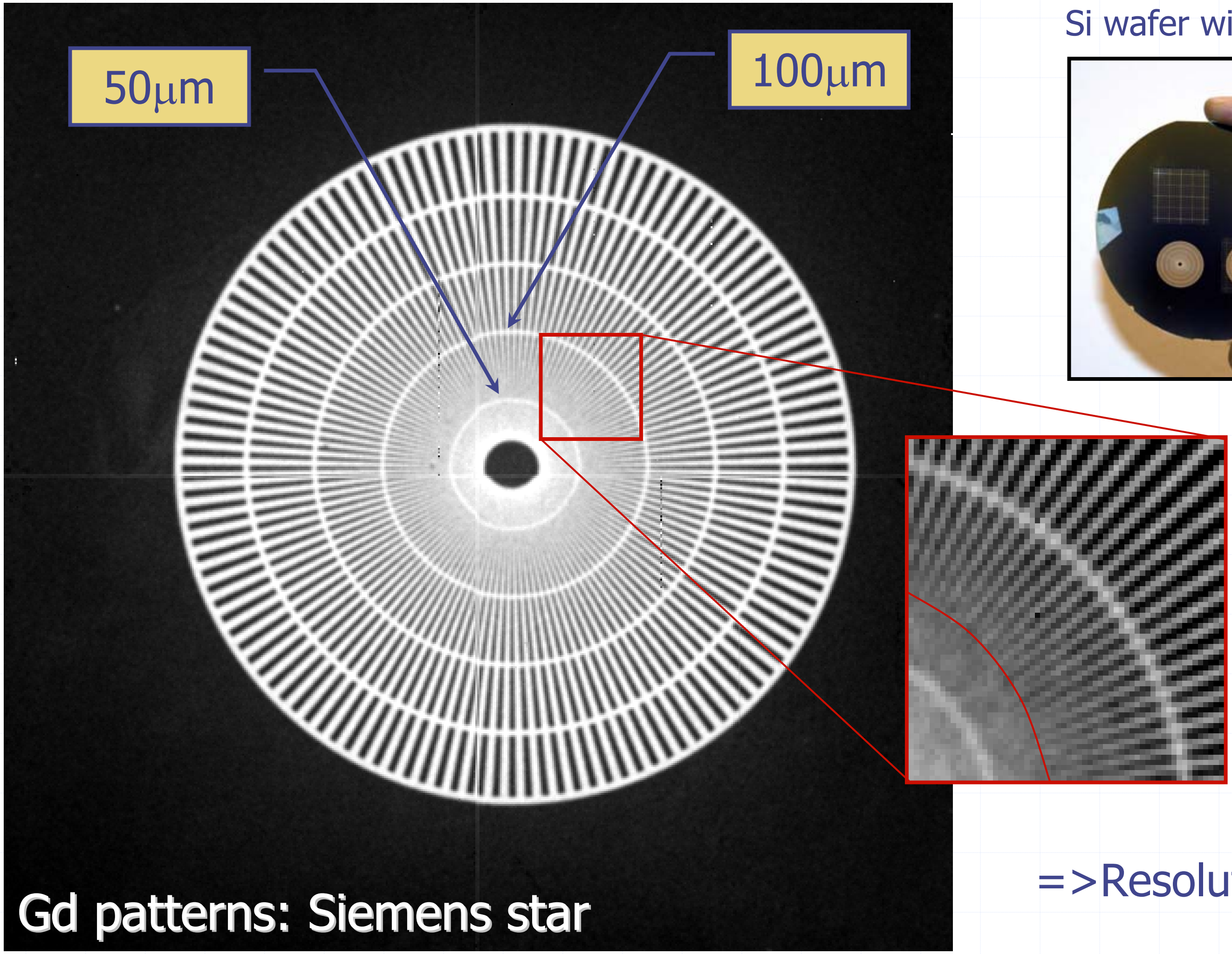
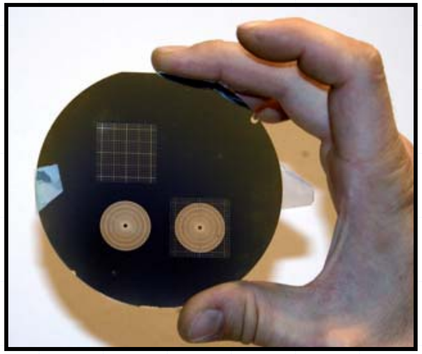


Si wafer with thin Gd pattern:



=>Resolution ~65µm!

Sample objects: wrist watch

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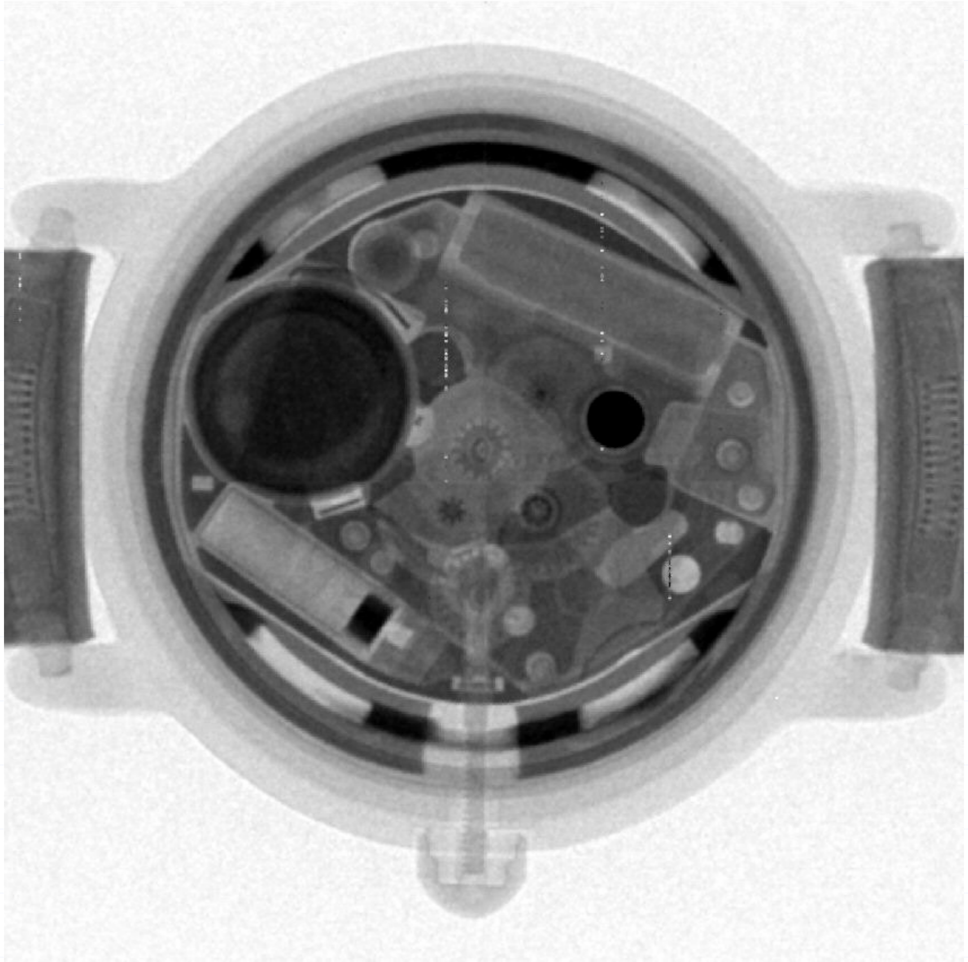
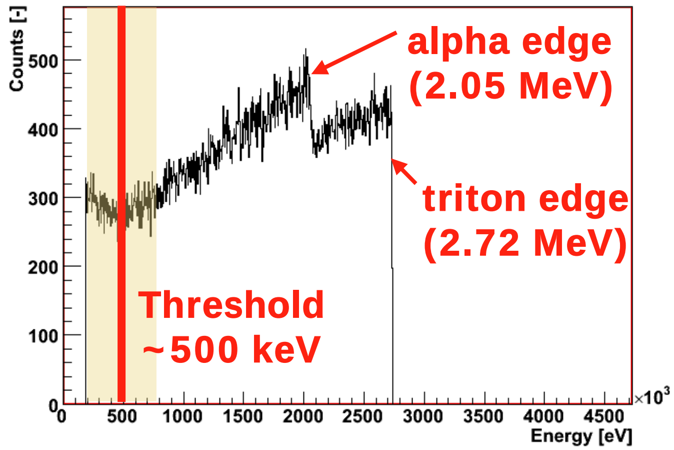
Medipix2 quad (at PSI, 2005):

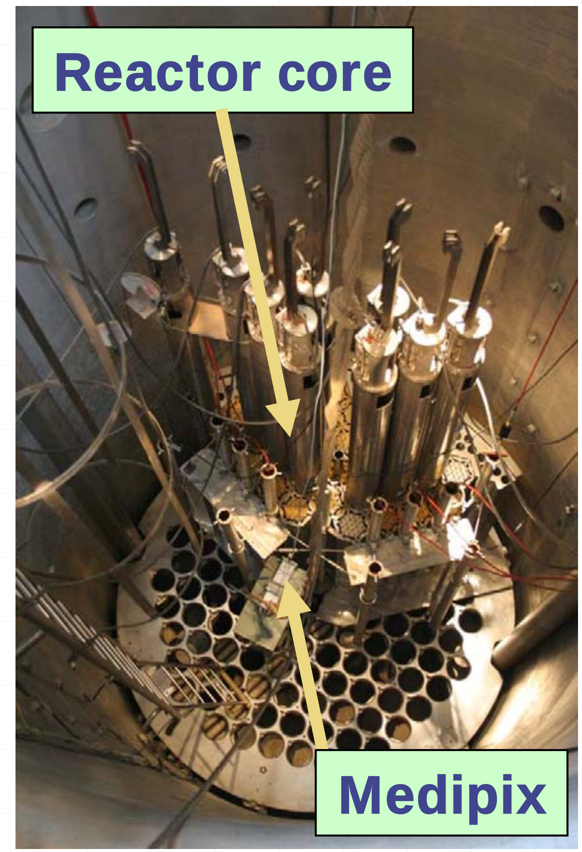


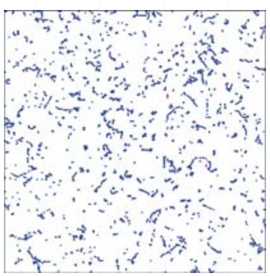
Good background suppression



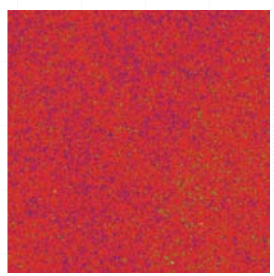
A typical spectrum of deposited energy in a planar detector with LiF converter

“zero power” reactor LR-0 at Rez near Prague

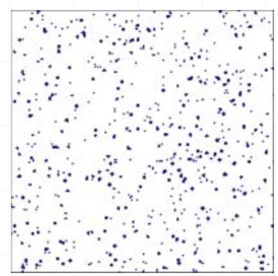




Reactor shut down



Reactor on



High threshold: only neutron clusters are visible

Background can be very effectively suppressed!

Drawback – a lower efficiency of the planar geometry

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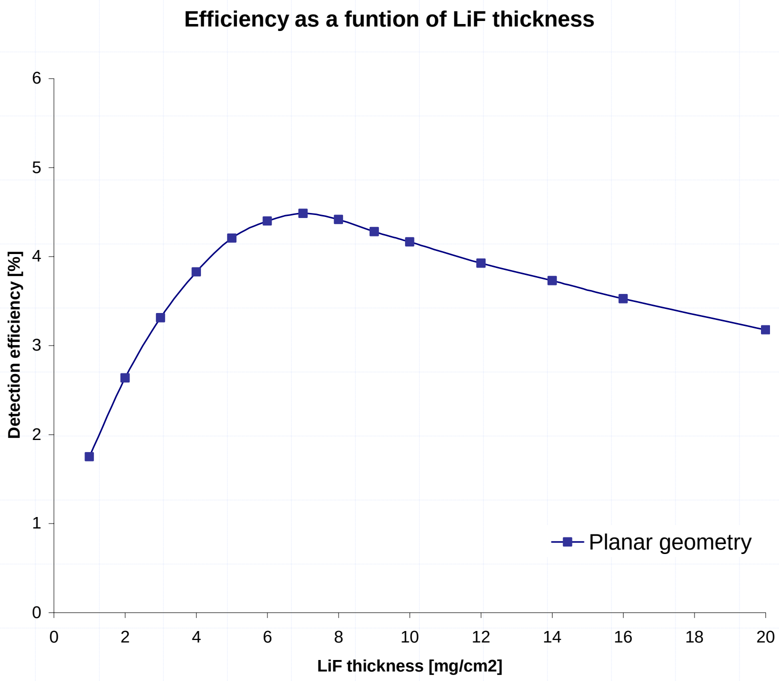
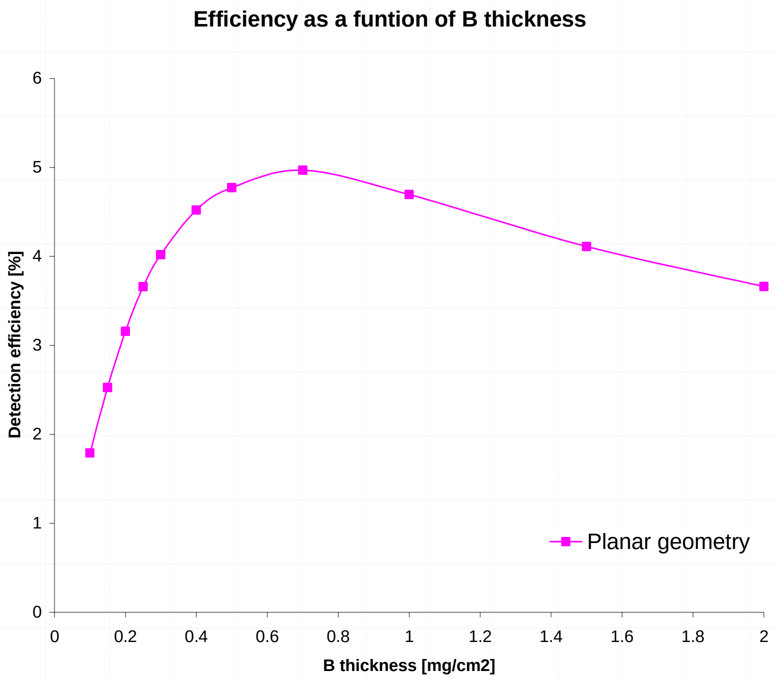
^{6}LiF, enrichment 90%



Amorphous ^{10}B, enrichment 80%



Efficiencies are comparable. Higher cross section of ^{10}B does not spawn a significant increase of efficiency.

Detection efficiency of the planar detector can not be more than ~5%!

Obverse and adverse irradiation

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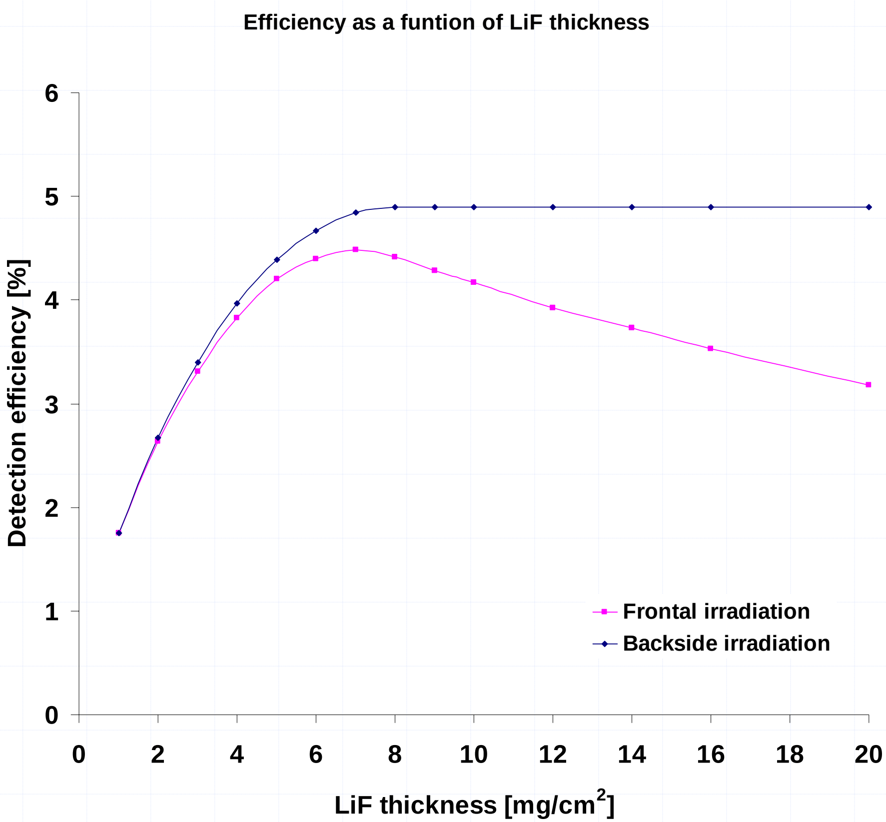

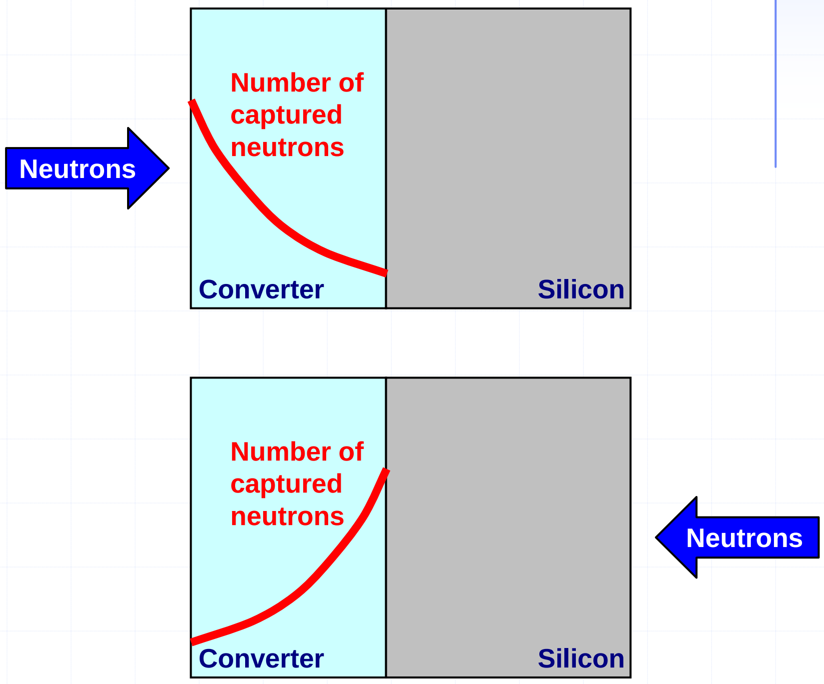

Irradiation from back side is useful especially when comparing different detectors and converters – the effect of self-shielding and the necessity of precise converter layer thickness control are eliminated.

Measured and simulated spectra of deposited energy

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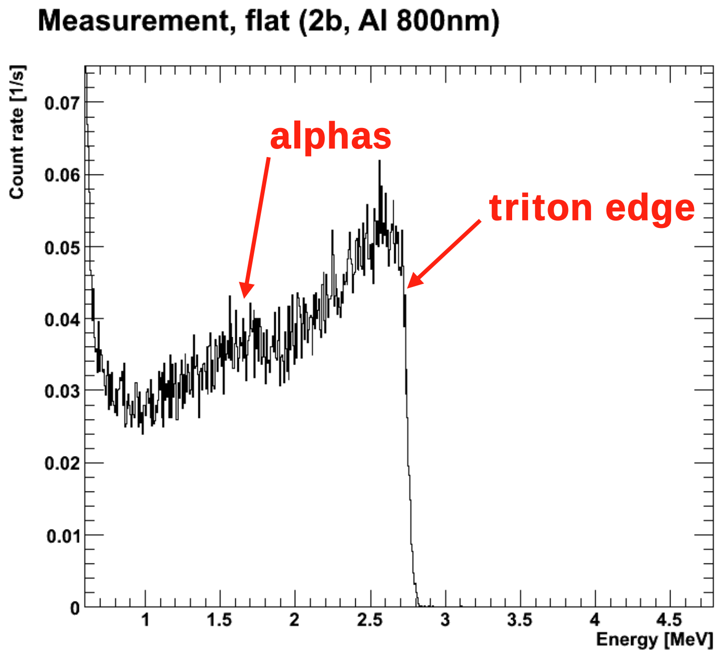
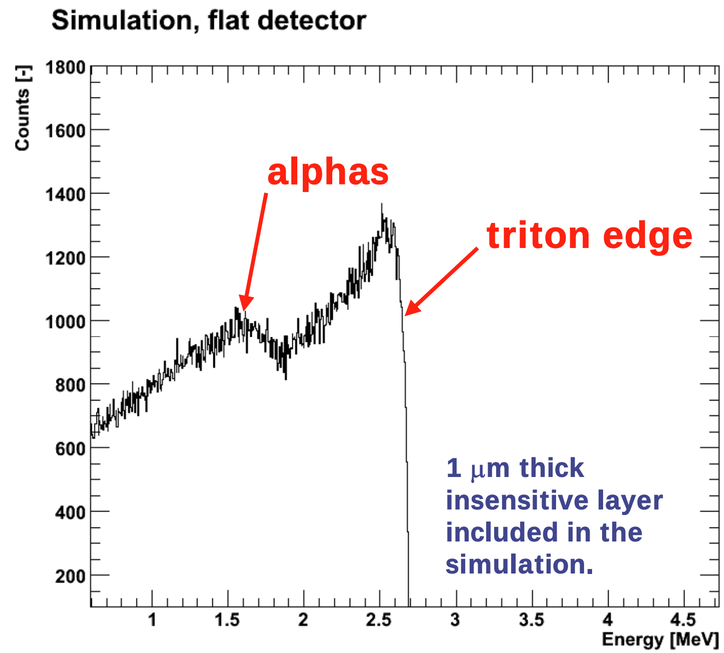
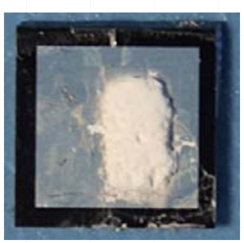
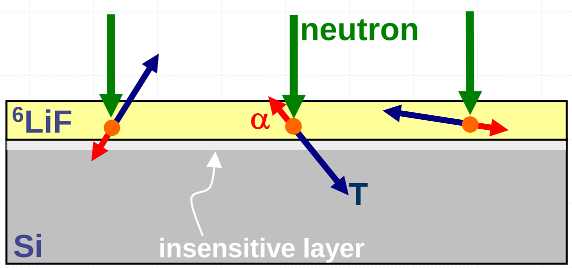






Fabricated at Mid-Sweden University, Sundsvall



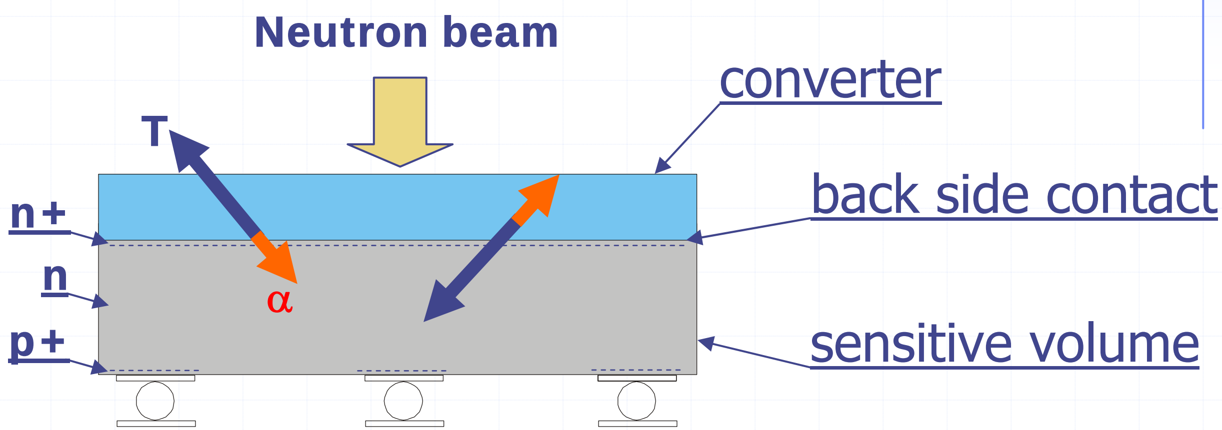
T and α always fly in opposite direction => no events above 2.72 MeV

Neutron beam parameters:

Horizontal channel (neutron guide) of the LVR-15 nuclear research reactor at Nuclear Physics Institute of the Czech Academy of Sciences at Rez near Prague. Intensity about 10^6 neutrons/(cm^{2}s) at reactor power of 8MW

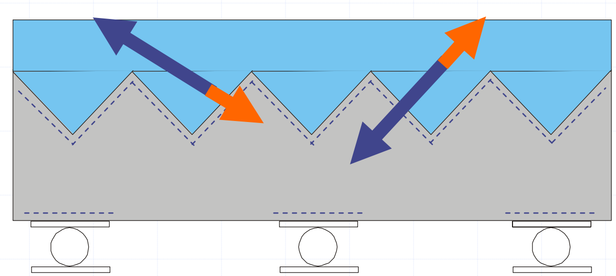
2D neutron array modification

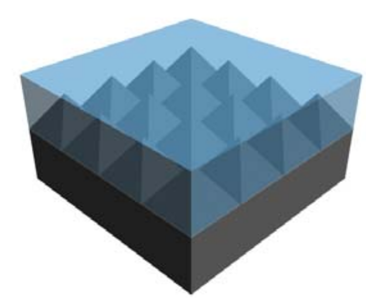
"Standard" 2D type



"Egg plate" 2D type

(with enlarged surface to increase
the detector efficiency)





Neutron array modification

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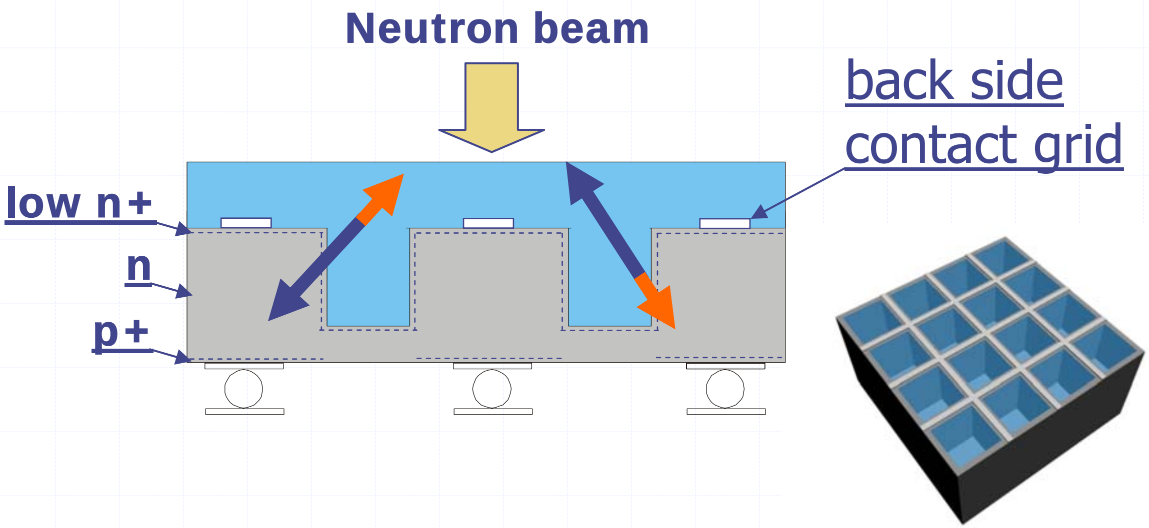
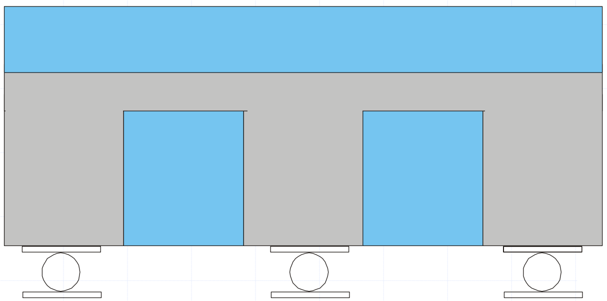
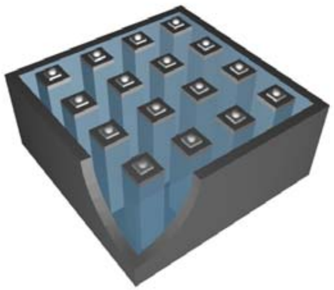
"Channel" 2D type
(maximized filling)



"3D inverse" structure
(there are pillars instead of pores)



bottom view



Inverse pyramids

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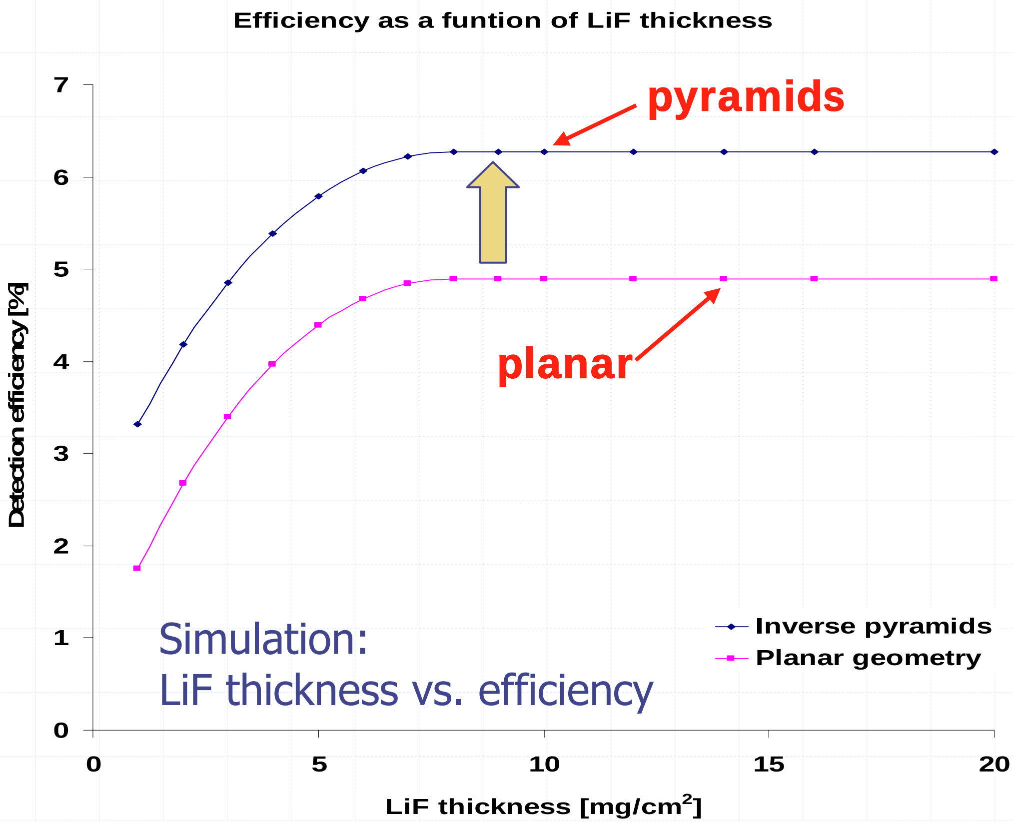

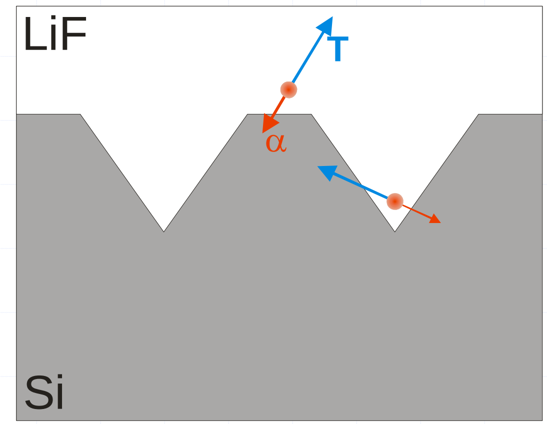

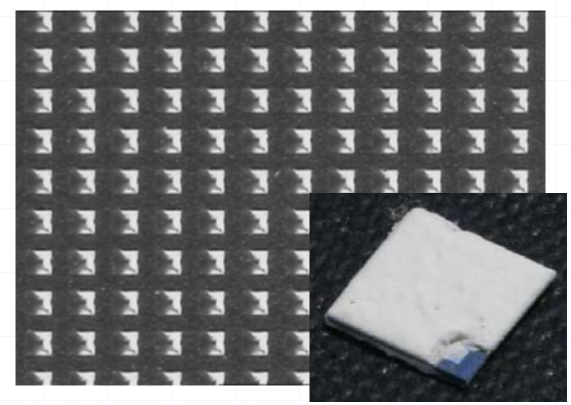

The pyramidal dips increase the overall detection efficiency from 4.9% to 6.3% (an increase of ~28%).

(samples from Sundsvall, Sweden)

Note: exposure time of a neutron imaging detector can be by 28% shorter to get the same SNR!

Measured and simulated spectra of deposited energy

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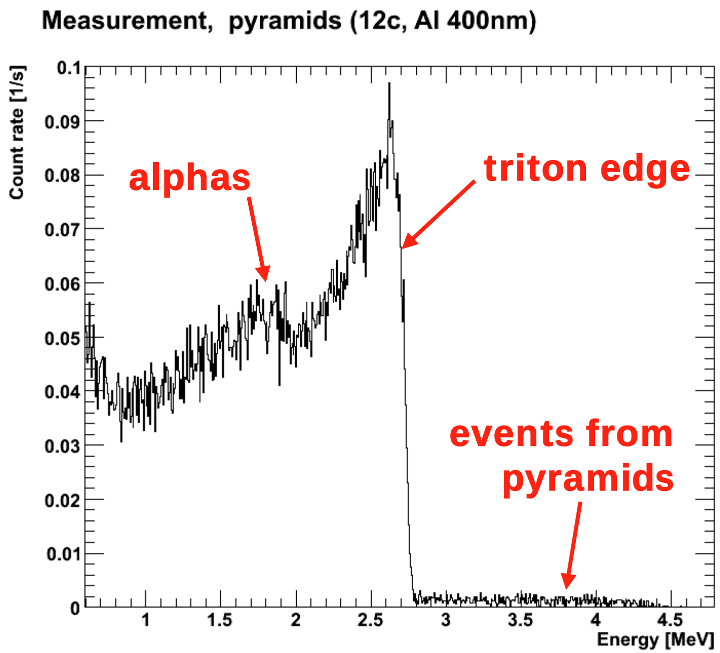
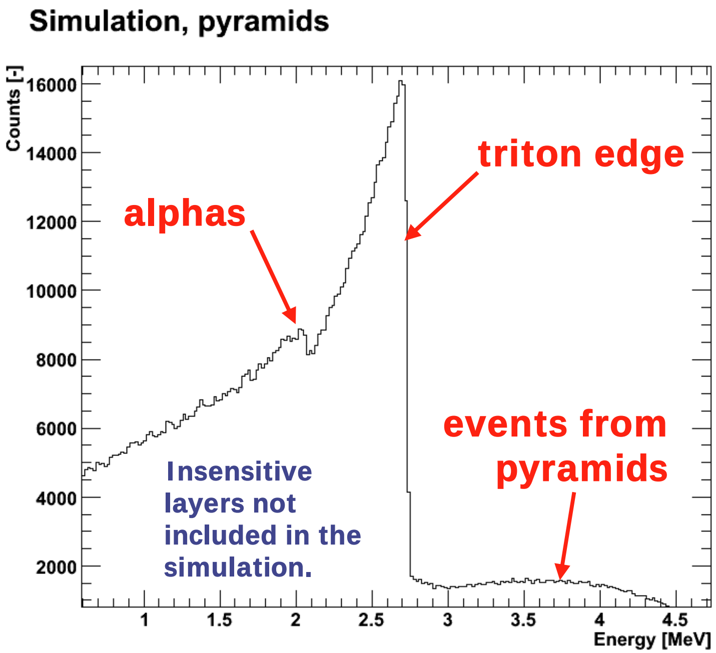
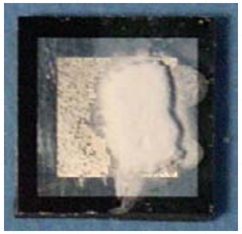
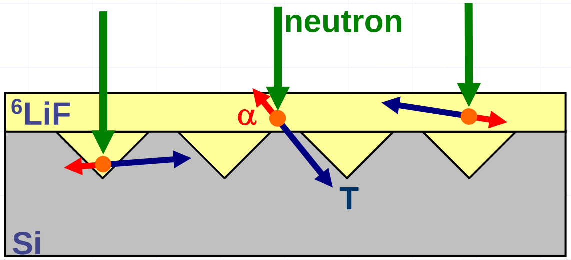






Fabricated at Mid-Sweden University, Sundsvall



T and α from pyramids can reach Si at the same time => events above 2.72 MeV

Neutron beam parameters:

Horizontal channel (neutron guide) of the LVR-15 nuclear research reactor at Nuclear Physics Institute of the Czech Academy of Sciences at Rez near Prague. Intensity about 10^6 neutrons/(cm^{2}s) at reactor power of 8MW

3D geometry arrays

- comparison of cylindrical vs. square ^{6}LiF converter

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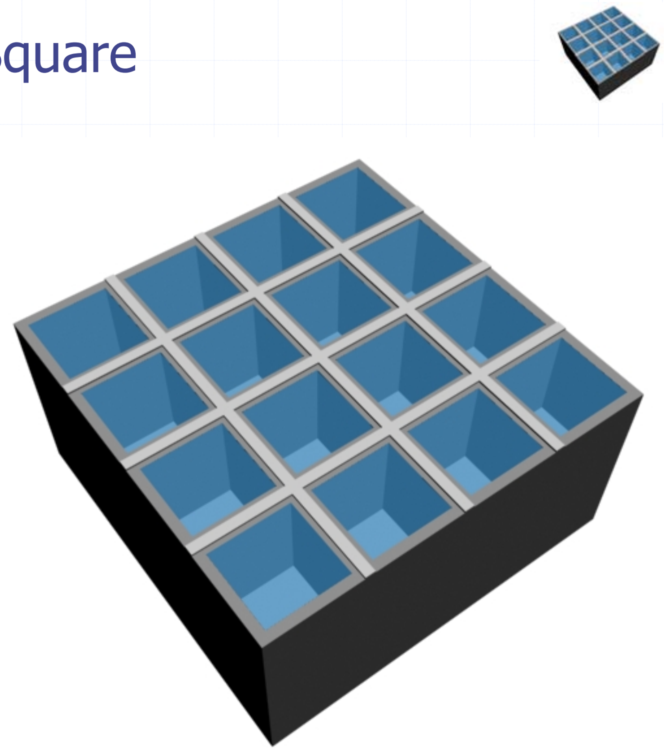
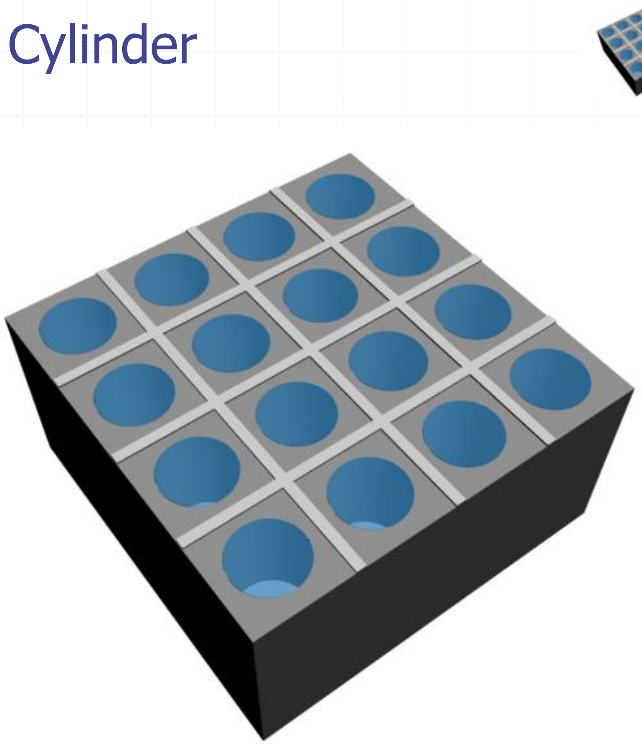
Fixed wall thickness – variance in the converter / cell size

Square



Cylinder



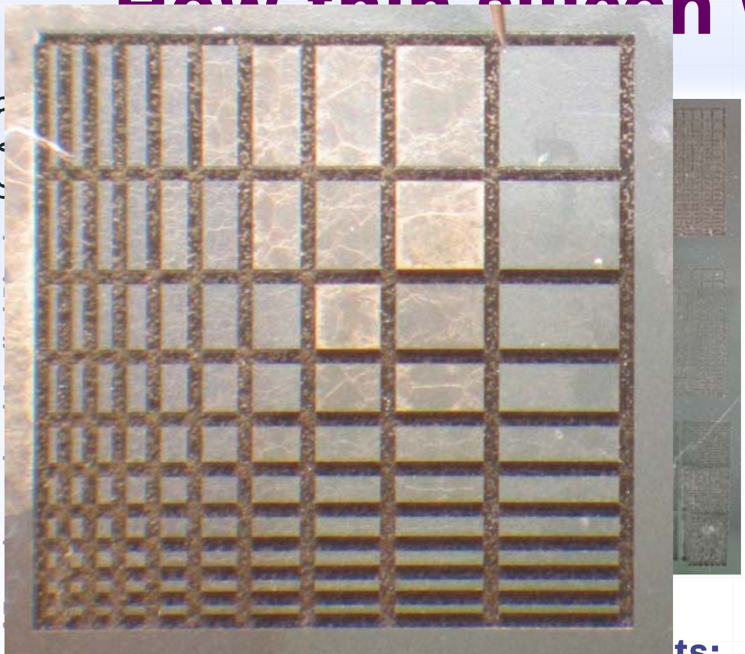
Maximal efficiency: ~32%

Maximal efficiency: ~27%

The optimal pore size: from 30 to 70 μm depending on ^{6}LiF converter filling density.
It is achievable with current semiconductor technologies.

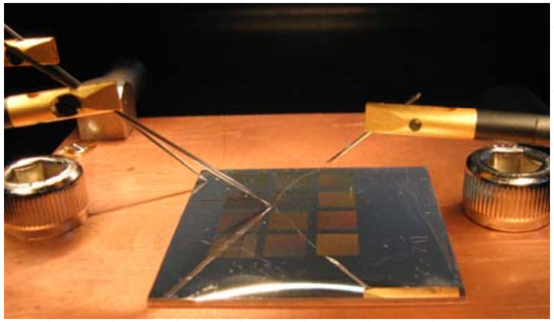
A question unanswered by simulations: **What is a feasible wall thickness?**

How thin silicon walls still work?



Various pillars with sizes ranging from 808 μm to 10 μm.

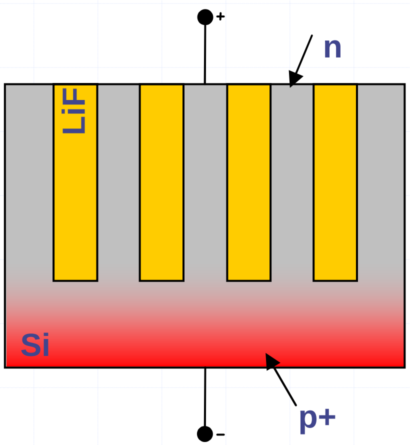
Heights of pillars are 80 and 200 μm.



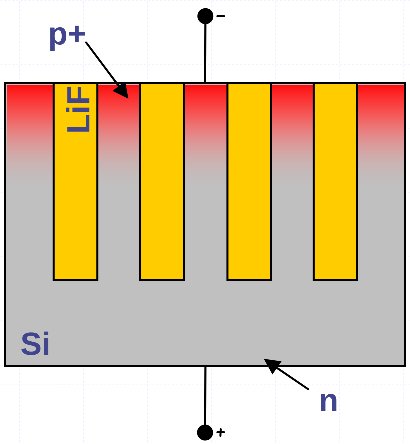
A sample contacted with probes

Samples were prepared by Chris Kenney

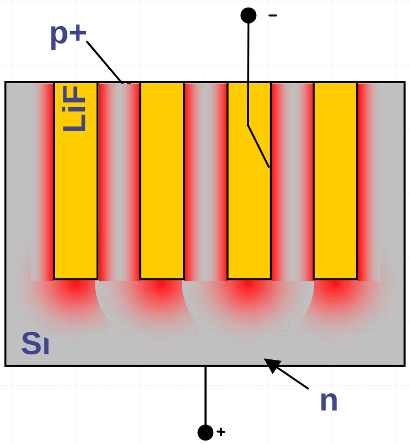
Possible pn junction placements:



pn junction on bottom

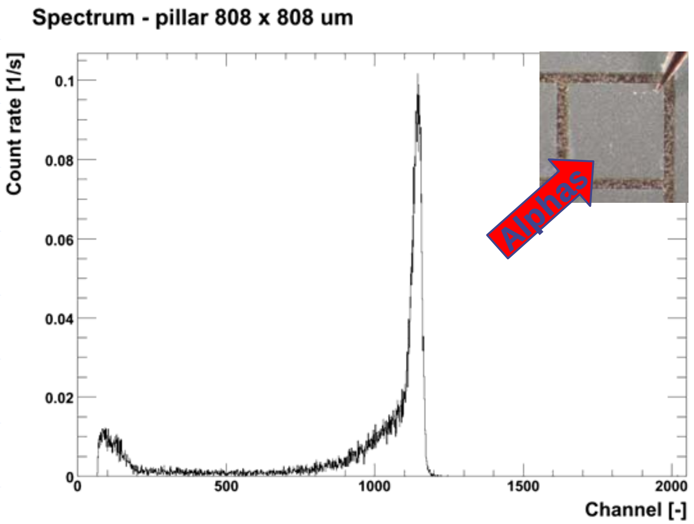


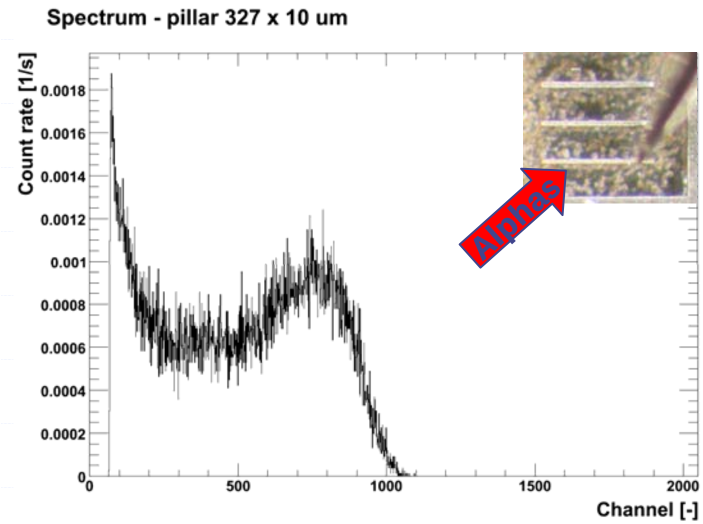
pn junction on top

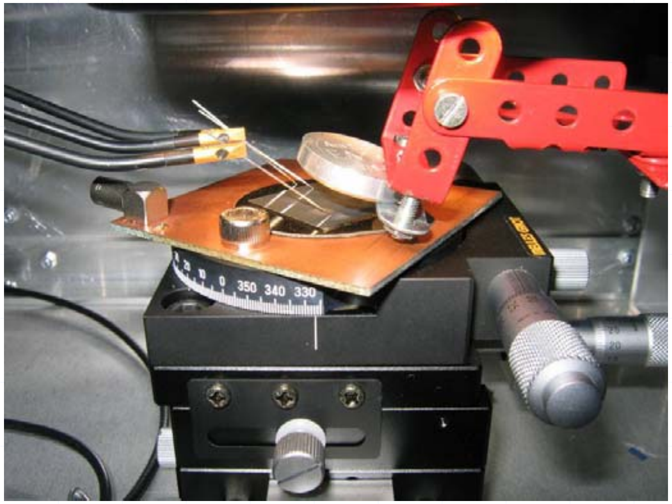


pn junction on pore surfaces

^{241}Am alpha spectra of 80 μm tall pillars







Range of 5.41 MeV alphas from ^{241}Am in silicon is 28.2 μm => they deposit only part of their energy in the thin wall.

Relative peak position

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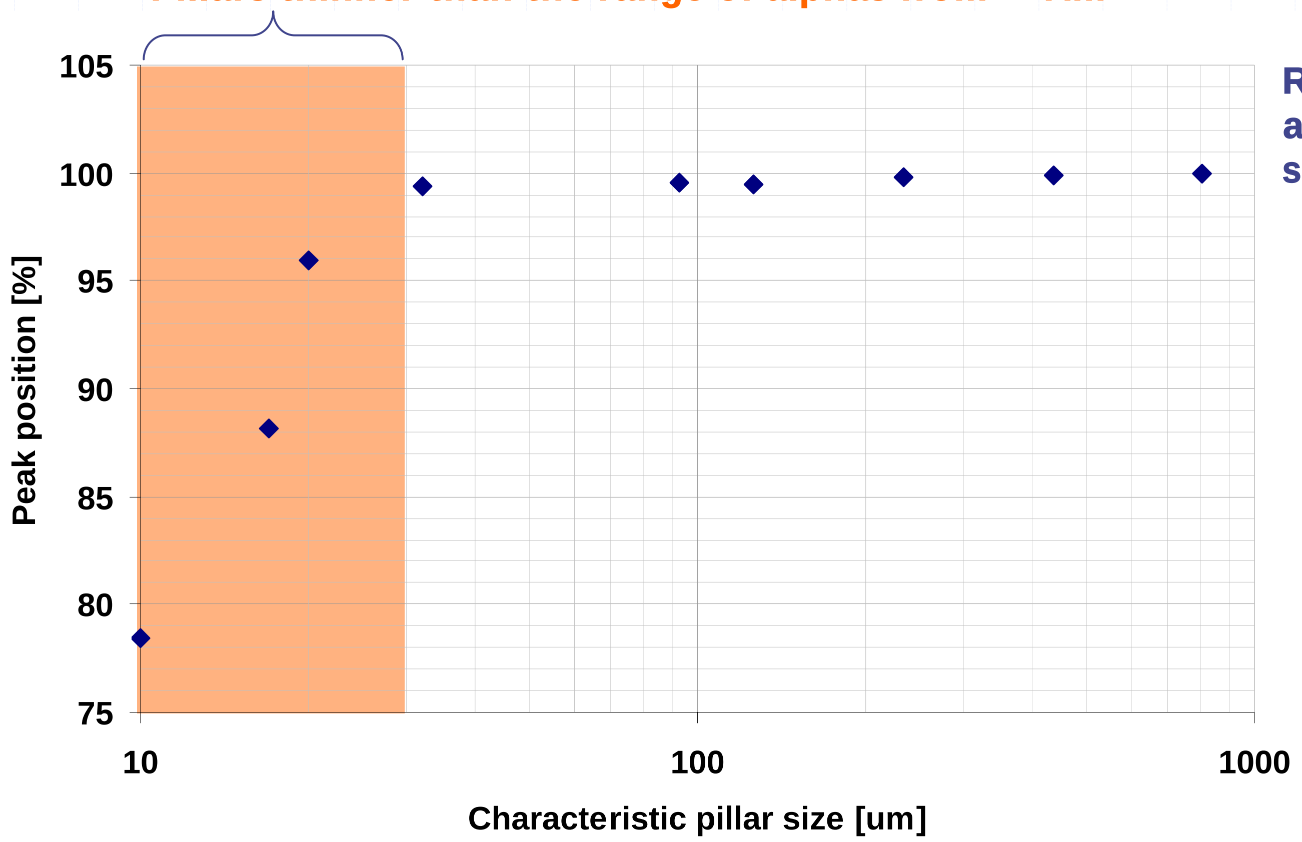
Pillars thinner than the range of alphas from ^{241}Am



Range of 5.41 MeV alphas from ^{241}Am in silicon is 28.2 μm.

An important conclusion of this measurement:

10 μm wide and 80 μm high silicon walls still work fine as a detector.

Conclusion and future work

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Behind us:

- Tests of planar single pad detectors with thermal neutrons
- Validation of simulations
- Simulations of 3D structure detection efficiency
- Measurements of silicon microstructures as heavy charged particles detectors
- Tests of structure filling

Ahead of us:

- Tests of 3D single pad detectors with thermal neutrons
- Medipix device with 3D thermal neutron detector
- Devices for fast neutrons
- Optimization of structures for different applications
- ...

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Thanks a lot for your attention

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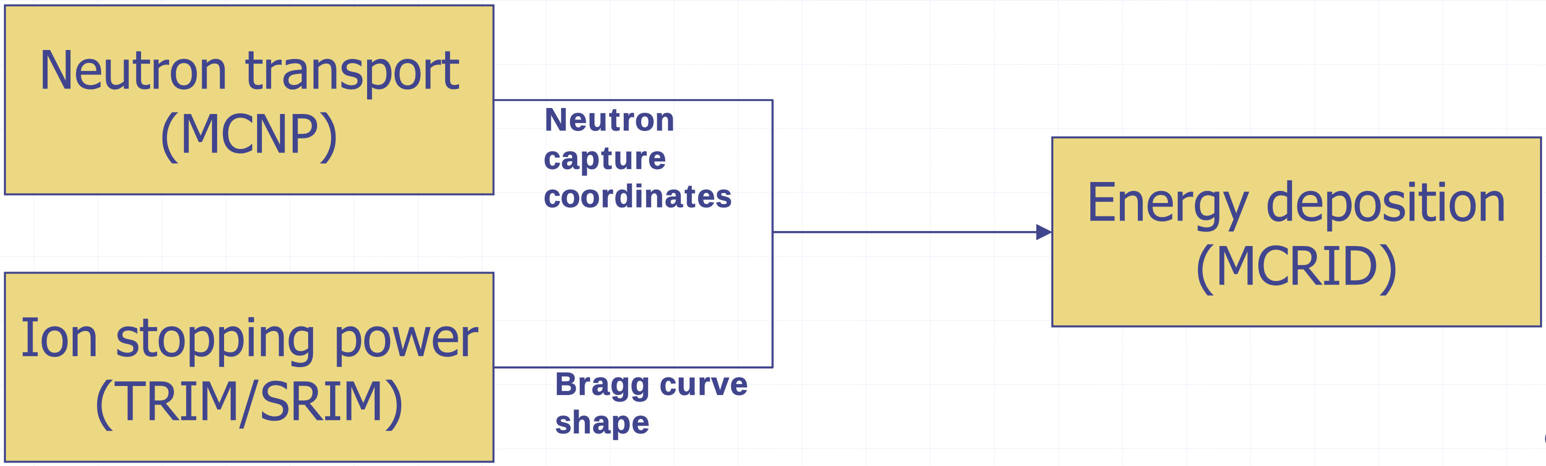
Backup slides

Simulation package



Our Monte-Carlo code (MCRID) samples directions of ions and simulates flight of them in matter. It performs plotting of deposited energy distribution and pulse height spectrum.

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Examples of created structures

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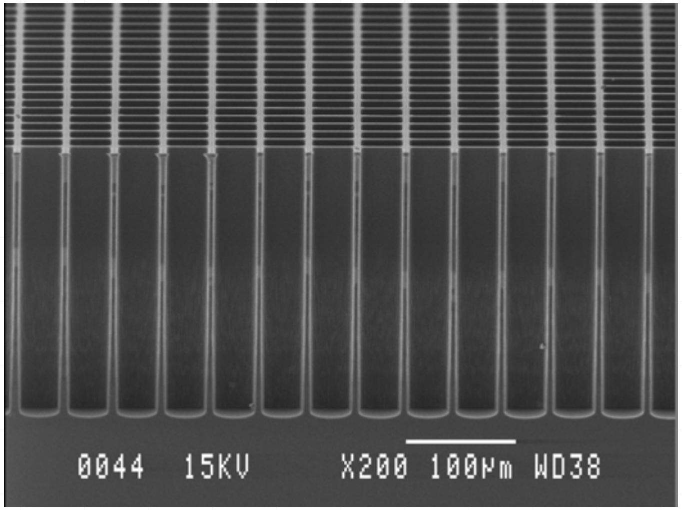
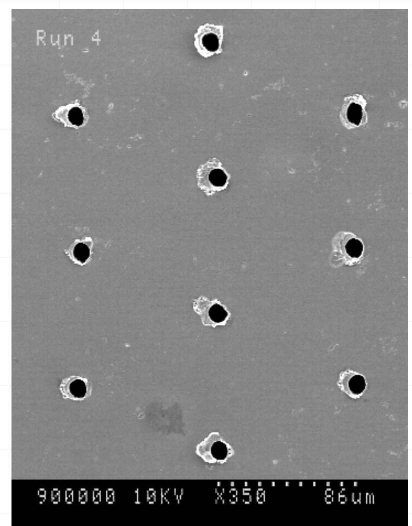


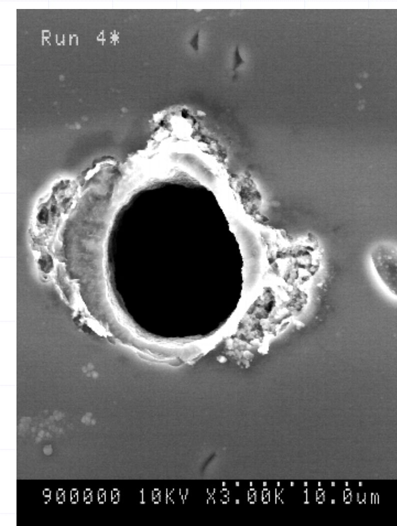
Photo-electrochemical etching

(KTH, Stockholm)

Laser ablation

(University of Glasgow)





3D stuffed detector

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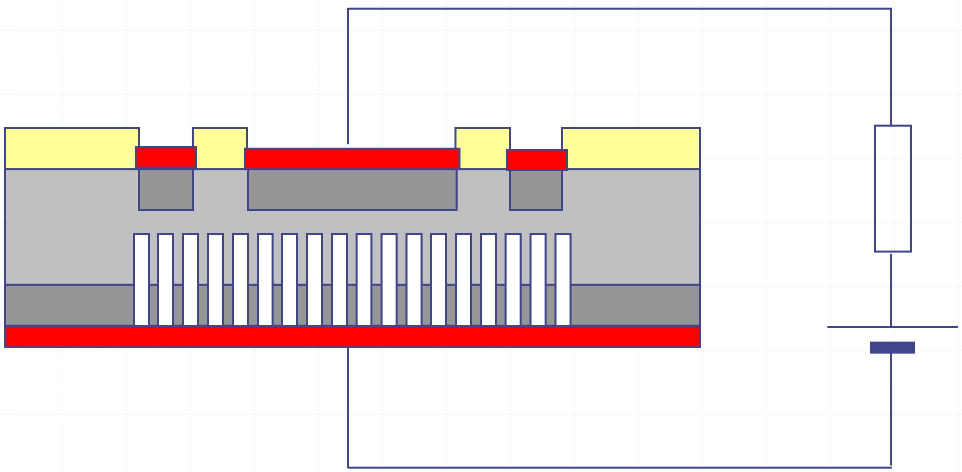
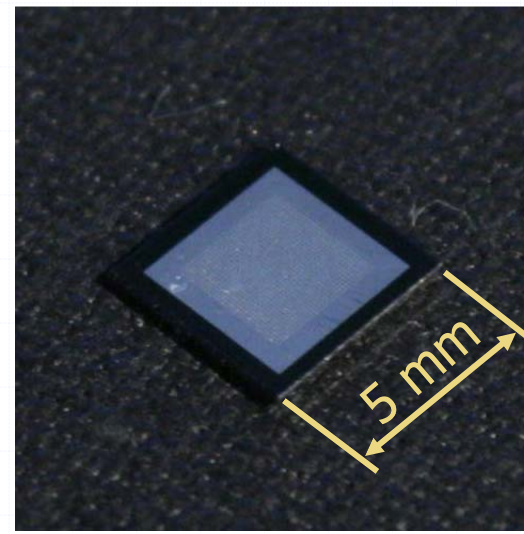
- **A next step in the development would be a 3D detector diode with etched pores filled with a neutron converter.**





3D stuffed detector → **intermediate step** → **"Inverse pyramids" detector (Sweden)**

3D geometry arrays

- comparison of cylindrical vs. square ^{10}B converter

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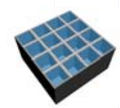
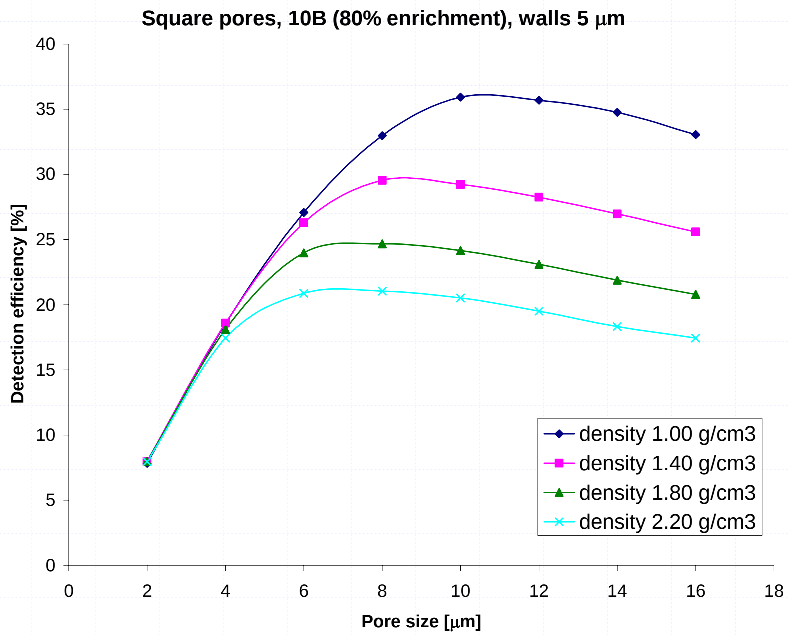
Fixed wall thickness – variance in the converter / cell size

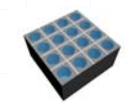
Square

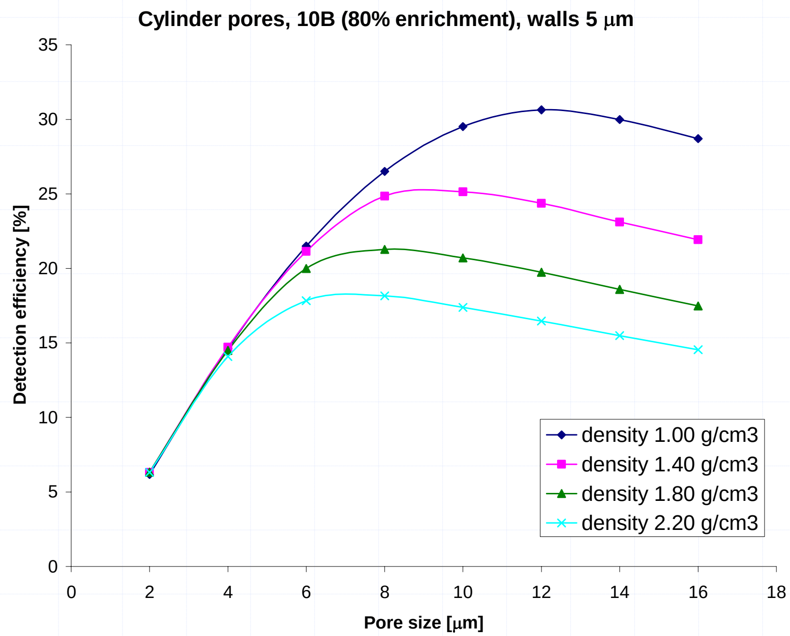




Maximal efficiency: ~36%

Cylinder





Maximal efficiency: ~31%

The detection efficiency is slightly higher than for ^{6}LiF, BUT the simulation does not include insensitive layers (passivation, contacts, etc.) which will turn the results in favor of ^{6}LiF.

The unanswered question still remains: **What is a feasible wall thickness?**

^{241}Am alpha spectra of 80 μm tall pillars

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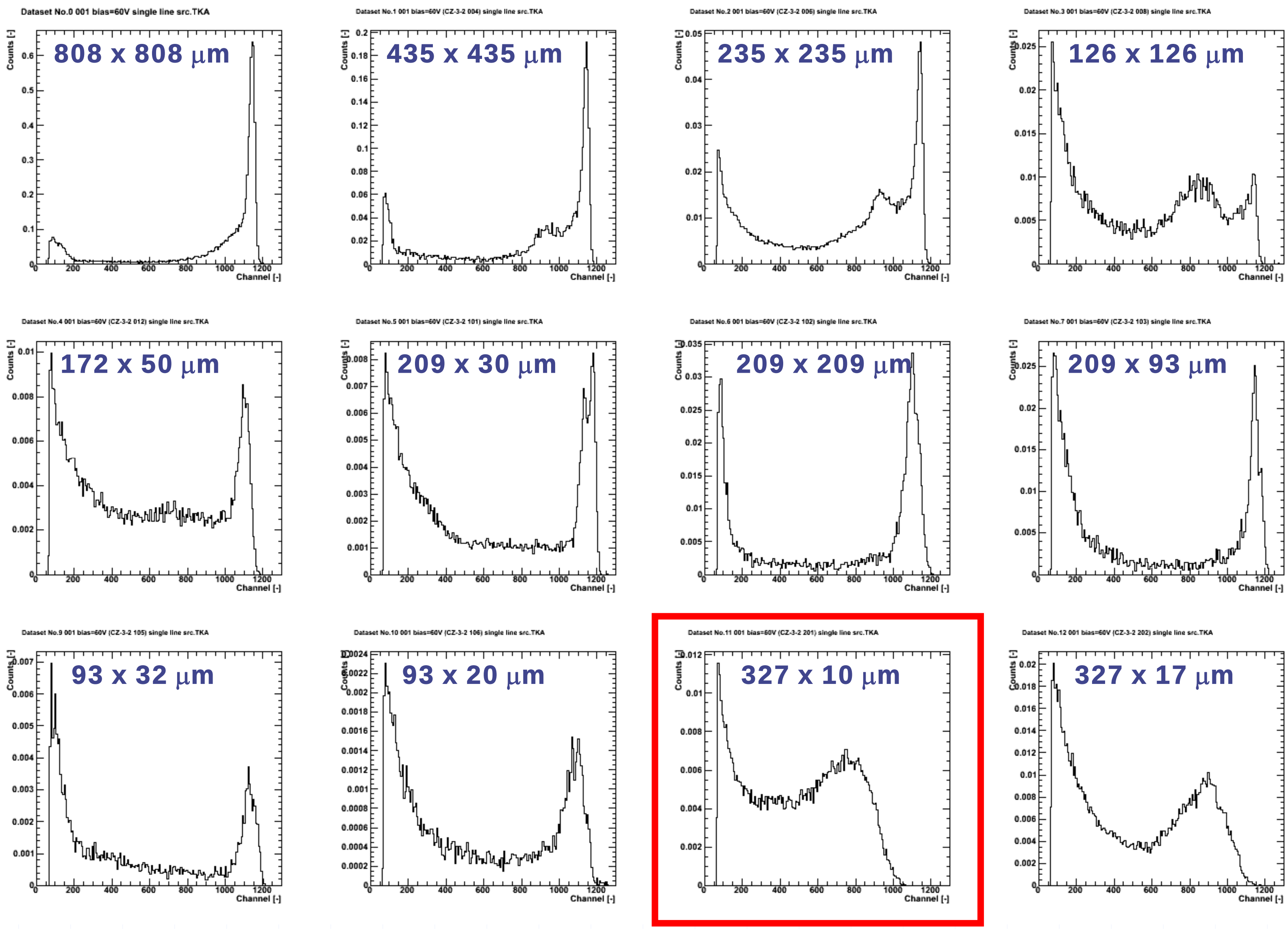

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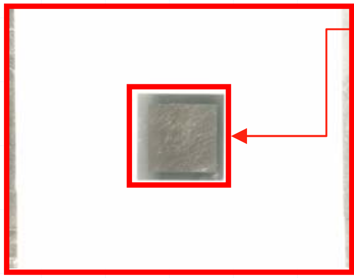
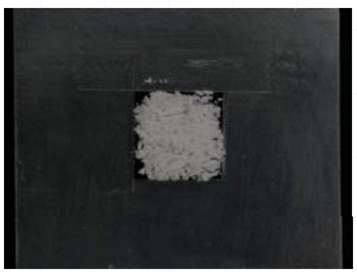
Pores filling using pressure



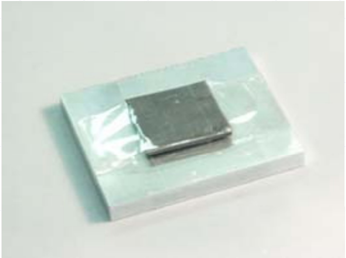
Empty pores



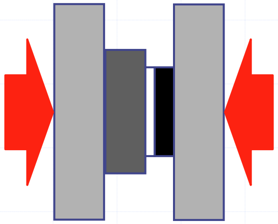
Poured powder

Covered by foil

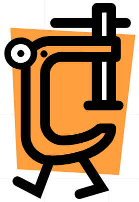
Lead hob



Final preparation ready for pressing



Pressing



Pores filling using pressure

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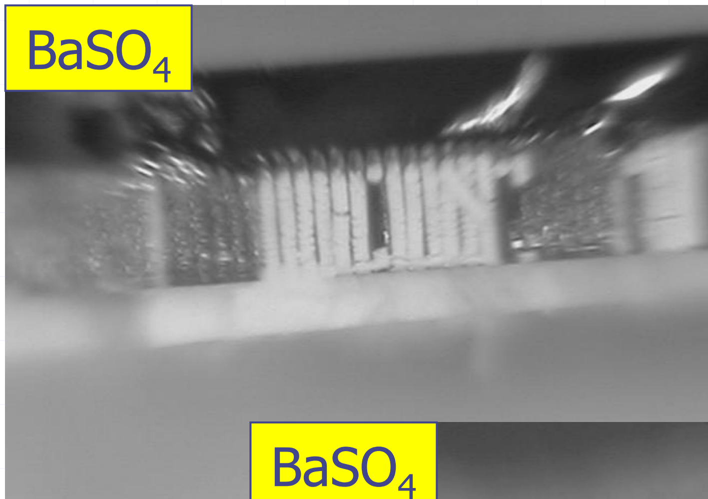

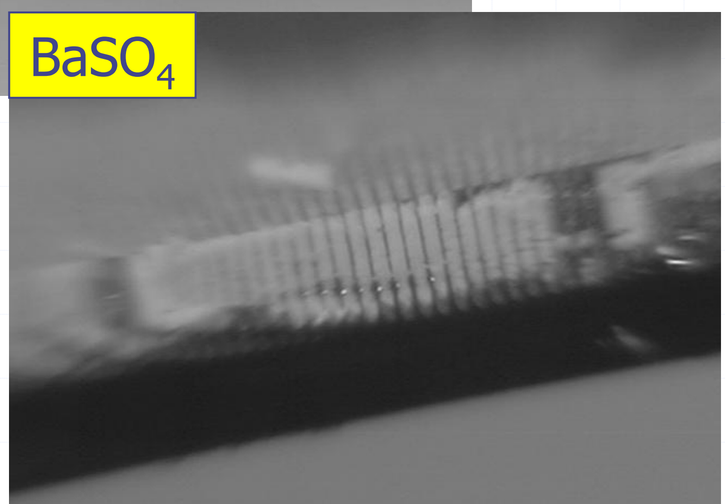

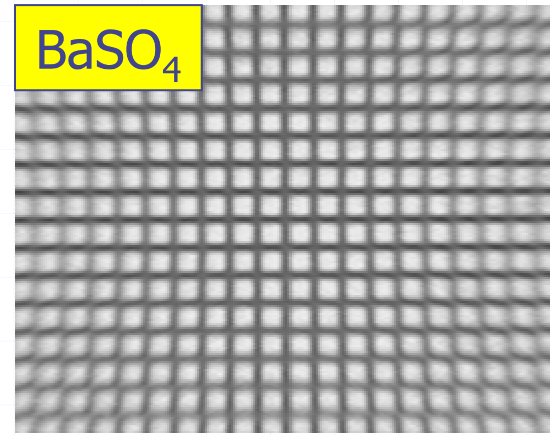

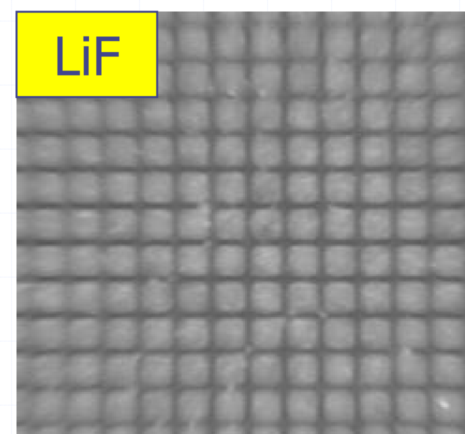

Pores filling using pressure

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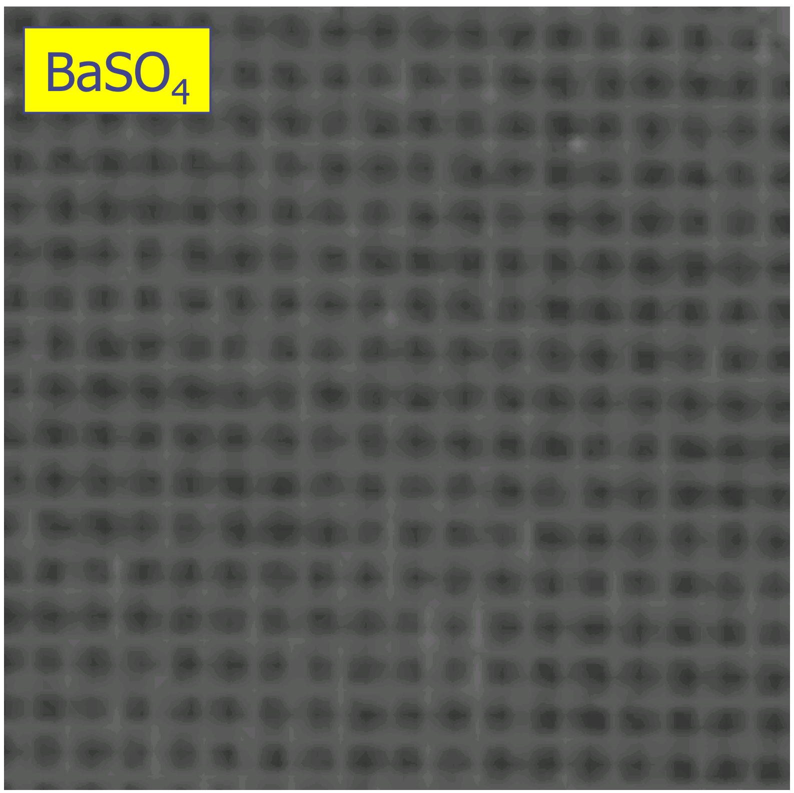
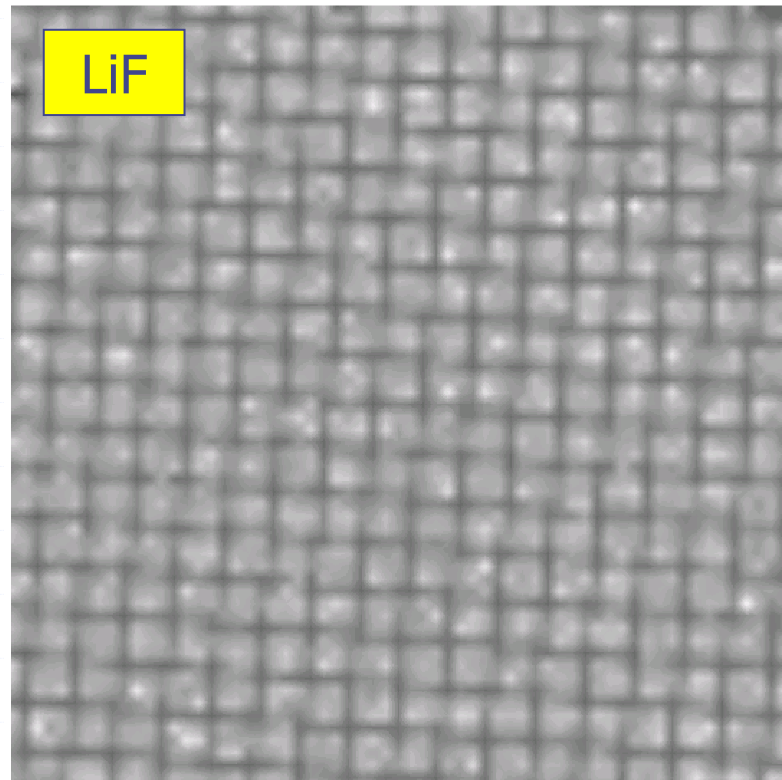
Roentgenogram of filled structures





Estimated average filling depth is 150μm