CdTe Hybrid Pixel Detector for Imaging with Thermal Neutrons

J. Jakubek, G. Mettivier, M.C. Montesi , S. Pospisil, P. Russo, J. Vacik

Institute of Experimental and Applied Physics, Czech Technical University in Prague, Czech Republic

Dipartimento di Scienze Fisiche, Università di Napoli Federico II, and INFN, Sezione di Napoli, Italy

Nuclear Physics Institute, Academy of Science of the Czech Republic

Work carried out within the Medipix Collaboration and supported by "Access Program", Project: NPL-1006

Outline

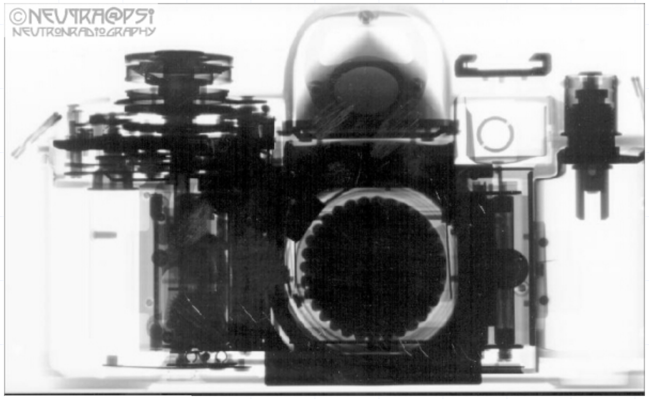
Institute of Experimental and Applied Physics
Czech Technical University in Prague

- Motivation: Neutron radiography
- Medipix2 device as a neutron imager
- CdTe Simulations
- Measurements
- Sample objects
- Comparison with other detectors
- Conclusions

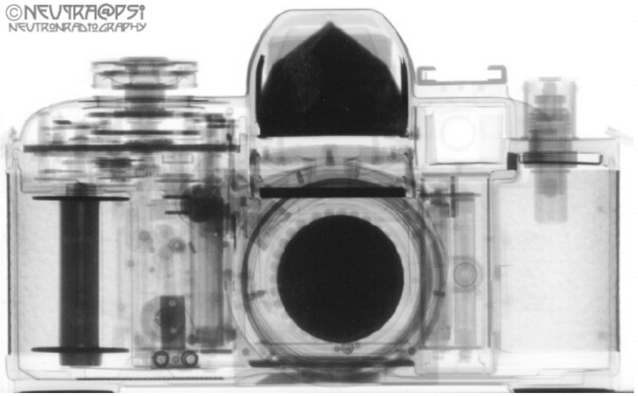
Why neutron radiography?

Institute of Experimental and Applied Physics
Czech Technical University in Prague

- 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.

X-rays

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Attenuation coefficients with X-ray [cm?^{1}]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 0.02																	He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77
Fr	Ra 11.80	Ac 24.47	Rf	Ha													

Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
*Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr x-ray

Legend

Attenuation coefficient [cm?^{1}] = sp.gr. * μ/δ
sp.gr.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.
μ/δ: J. H. Hubbell[+] and S. M. Seltzer Ionizing Radiation Division, Physics Laboratory National Institute of Standards and Technology Gaithersburg, MD 20899, http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html.

Thermal neutrons

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Attenuation coefficients with neutrons [cm?^{1}]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn
Fr	Ra 0.34	Ac	Rf	Ha													

*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	Es	Fm	Md	No	Lr neut.

Legend

$$\text{Attenuation coefficient [cm?}^{1}\text{]} = \frac{\sigma\text{-total} * \text{sp.gr.} * 0.6023}{\text{at.wt.}}$$

σ-total: JEF Report 14, TABLE OF SIMPLE INTEGRAL NEUTRON CROSS SECTION DATA FROM JEF-2.2, ENDF/B-VI, JENDL-3.2, BROND-2 AND CENDL-2, AEN NEA, 1994.
and Special Feature: Neutron scattering lengths and cross sections, Varley F. Sears, AECL Research, Chalk River Laboratories Chalk River, Ontario, Canada KOJ 1JO, Neutron News, Vol. 3, 1992, http://www.ncnr.nist.gov/resources/n-lengths/list.html.

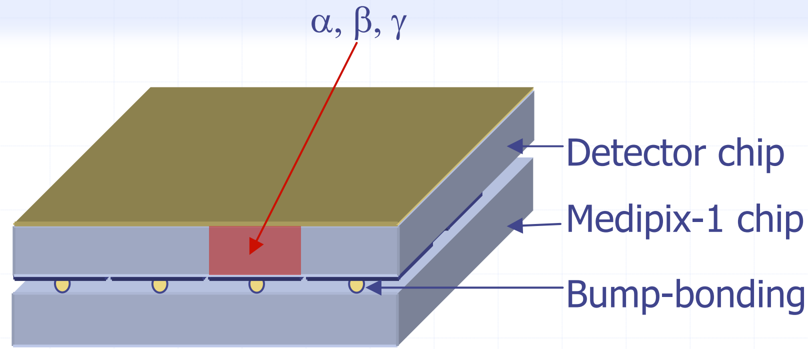
sp.gr.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

at.wt.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

Medipix device

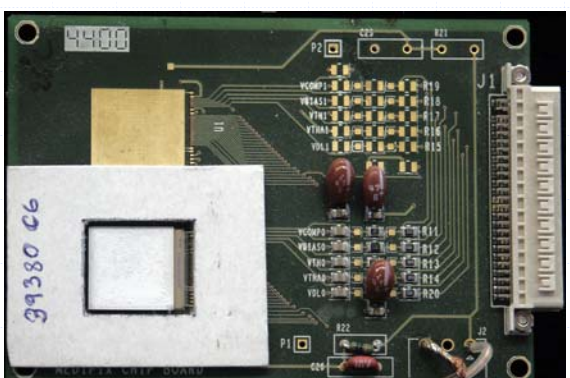
Institute of Experimental and Applied Physics
Czech Technical University in Prague

- Planar semiconductor pixel detector (Si, GaAs, CdTe, …)
- Bump-bonded to Medipix readout chip containing amplifier, double discriminator and counter in each pixel cell.



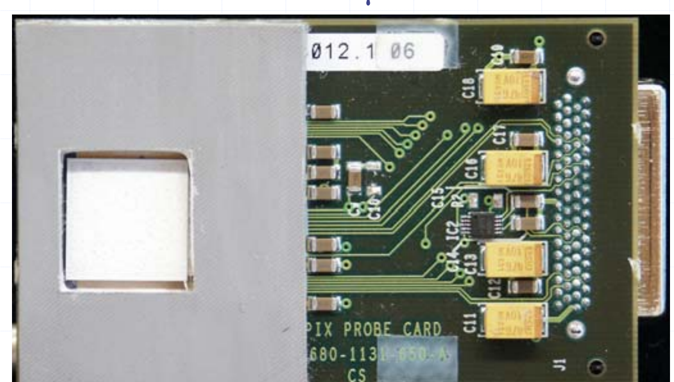
Medipix-1

Pixels: 64 x 64
Pixel size: 170 x 170 μm^2



Medipix-2

Pixels: 256 x 256
Pixel size: 55 x 55 μm^2



Adaptation of the Medipix device for slow neutron detection

Institute of Experimental and Applied Physics
Czech Technical University in Prague

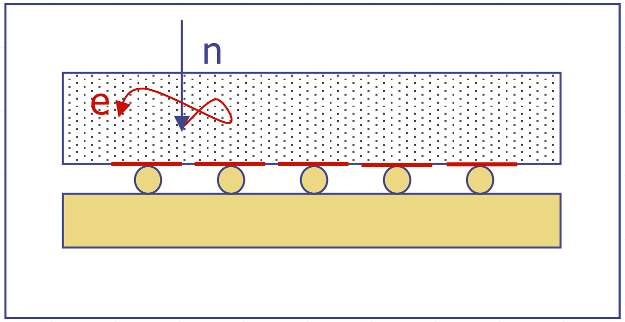
Principle:

Semiconductor pixel detector can barely detect slow neutrons directly.

⇒ Conversion of thermal neutrons to detectable radiation in a suitable material is needed.

Placement of a converter:

- on the sensor surface (coated detector),
- inside of the sensor volume (stuffed detector),
- converter is a component of the sensing material.



Converter materials: **Cross section**

^{6}Li:	$^6Li + n \rightarrow \alpha$ (2.05 MeV) + ^3H (2.72 MeV)		940 barns
^{10}B:	$^{10}B + n \rightarrow \alpha$ (1.47 MeV) + ^7Li (0.84 MeV) + γ (0.48MeV)	(93.7%)	
	$^{10}B + n \rightarrow \alpha$ (1.78 MeV) + ^7Li (1.01 MeV)	(6.3%)	3 840 barns
^{113}Cd:	$^{113}Cd + n \rightarrow {}^{114}Cd + \gamma$ (0.56MeV) + *conversion electrons*		26 000 barns
^{155}Gd:	$^{155}Gd + n \rightarrow {}^{156}Gd + \gamma$ (0.09, 0.20, 0.30 MeV) + *conversion electrons*		
^{157}Gd:	$^{157}Gd + n \rightarrow {}^{158}Gd + \gamma$ (0.08, 0.18, 0.28 MeV) + *conversion electrons*		~60 000 barns

Promising candidate: CdTe sensor

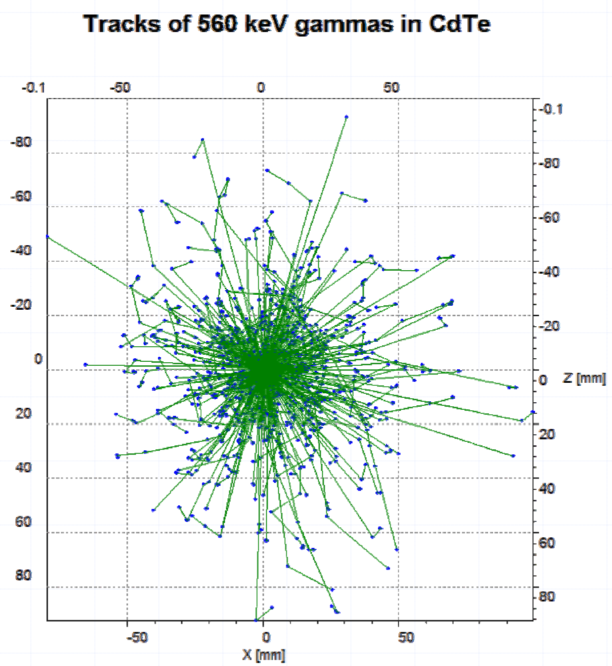
Institute of Experimental and Applied Physics
Czech Technical University in Prague

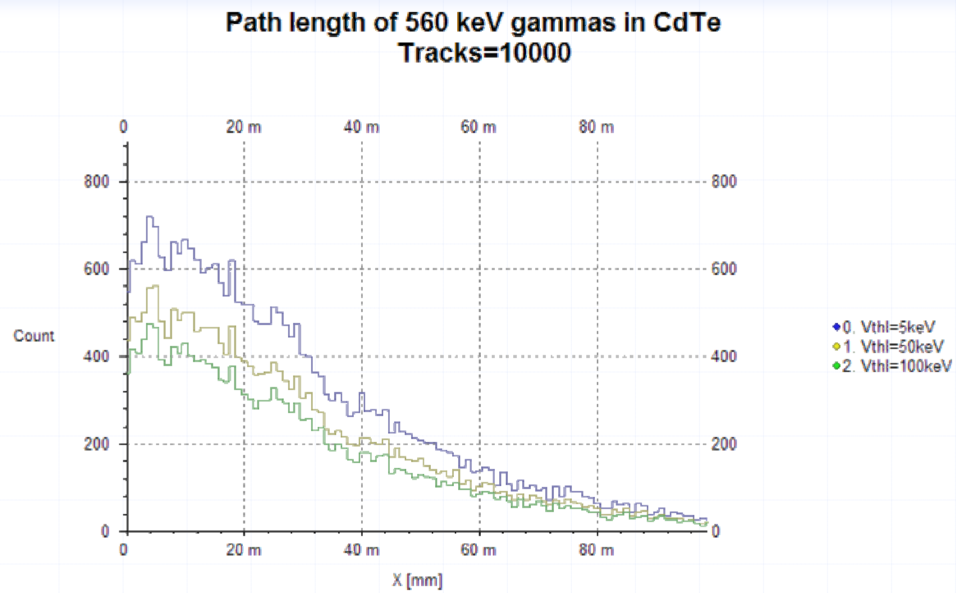
- 1mm thick CdTe bonded on Medipix2 chip
- Opaque for slow neutrons => almost all neutrons are captured
- Secondary radiation to be detected:
  - 558 keV photons
  - 558 keV electrons of internal conversion (about 3%)
- What imaging properties would have such neutron detector?

Monte-Carlo Simulations: Gamma Ray Interactions

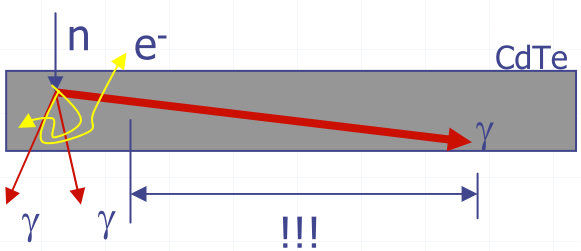
Institute of Experimental and Applied Physics
Czech Technical University in Prague

10 000 tracks of 560 keV photons in CdTe crystal have been simulated in MCNP.





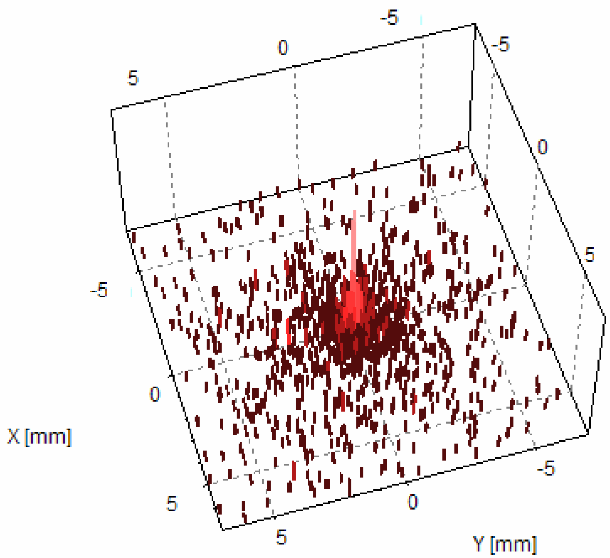
Range of 560 keV gamma photons exceeds Medipix size
=> background signal in images



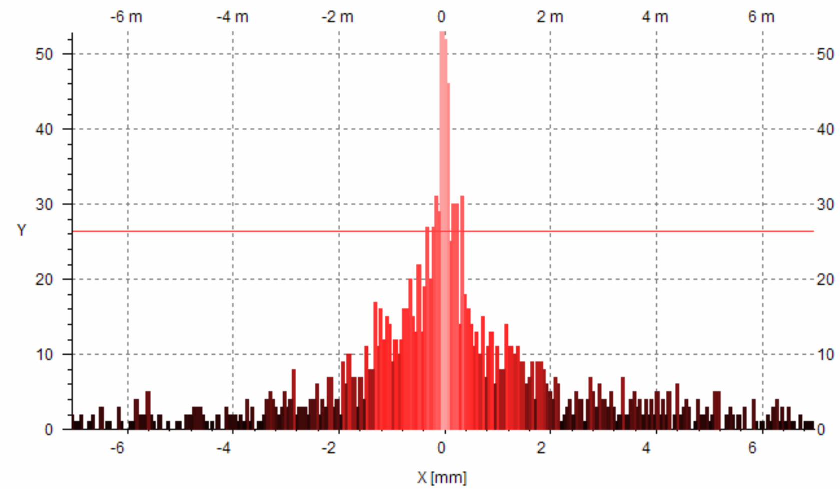
Point and Line Spread Functions

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Simulated point spread function caused by gamma detection



Simulated Line Spread Function caused by gammas

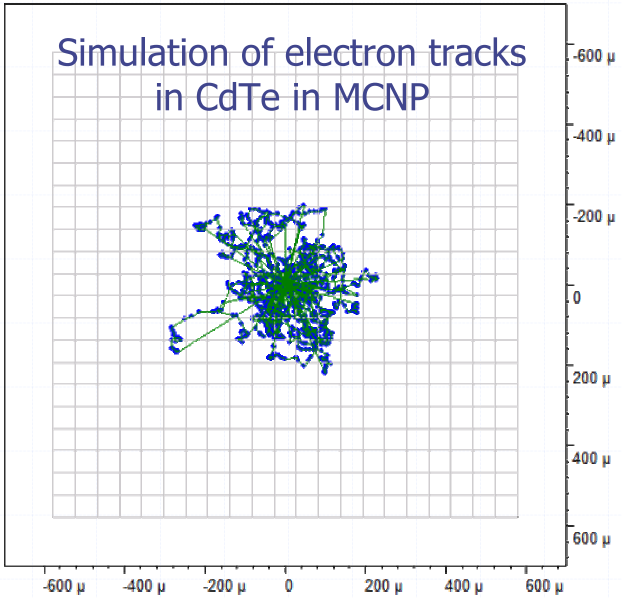


⇒ Spatial resolution in terms of FWHM of LSF via detection of gamma photons would be ~480μm

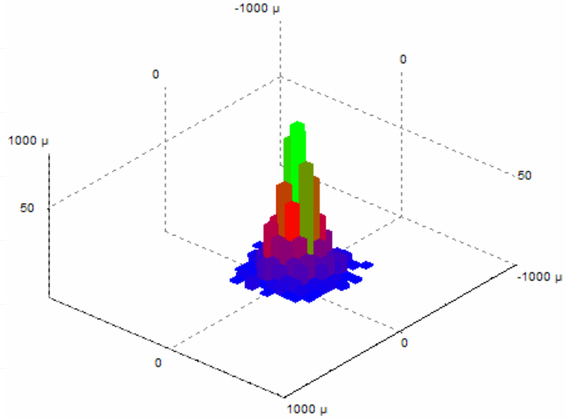
⇒ Background signal is generated in whole image

Monte-Carlo Simulations: Electron Interactions

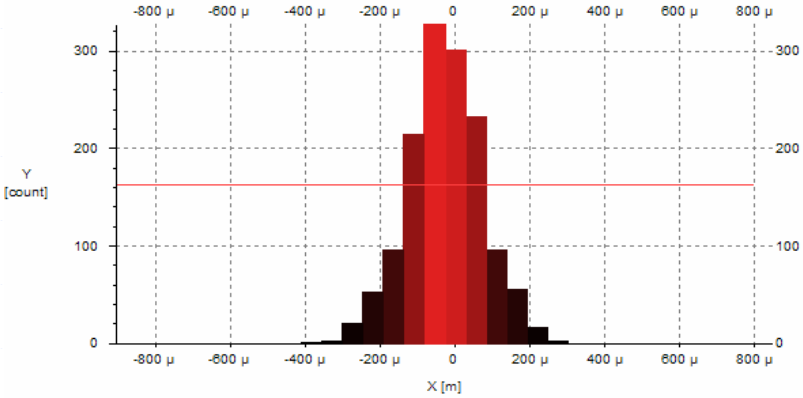
Institute of Experimental and Applied Physics
Czech Technical University in Prague



Point Spread function



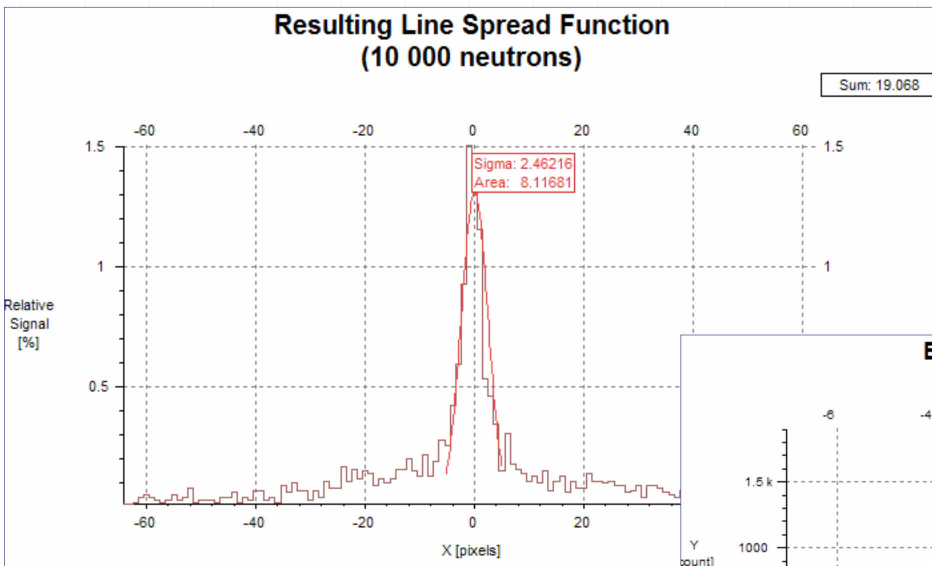
Line Spread Function



⇒ Expected spatial resolution via electron detection is ~200 μm

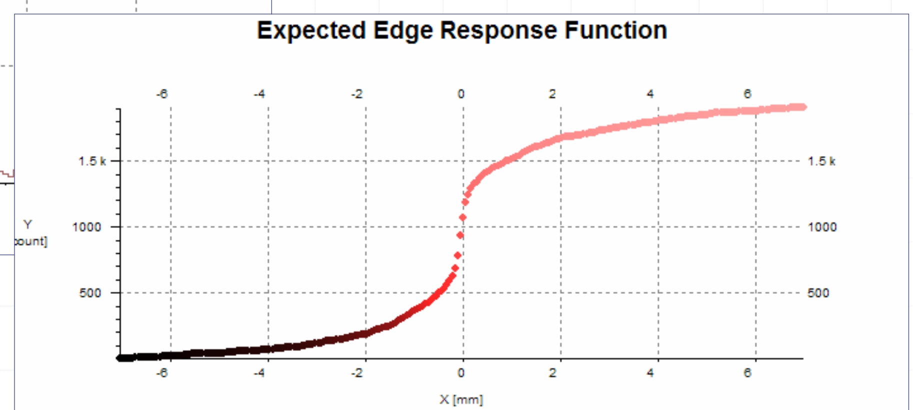
Combination

- Expected behavior of CdTe as a slow neutron detector is given by combination of previous results:



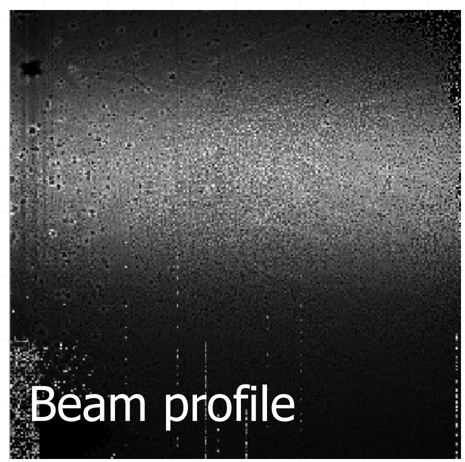
⇒Estimated spatial resolution is ~ 6 pixels which is 320μm.

⇒Estimated detection efficiency is ~ 20% but only 8% is usable for imaging.

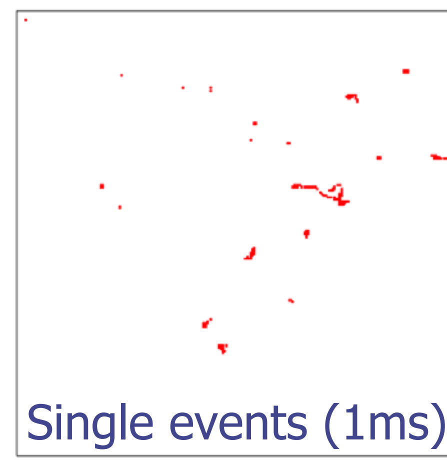


Tests with Thermal Neutrons

- Horizontal channel of the LVR-15 nuclear research reactor at Nuclear Physics Institute of the Czech Academy of Sciences at Rez near Prague.
  - Intensity is about 10^7 neutrons/cm^2s (at reactor power of 8MW)
  - Beam Cross section: 4 mm (height) x 60 mm (width)
  - The divergence of the neutron beam is < 0.5°
- Detector setting:
  - Bias voltage = 250V
  - Variable threshold level



Beam profile

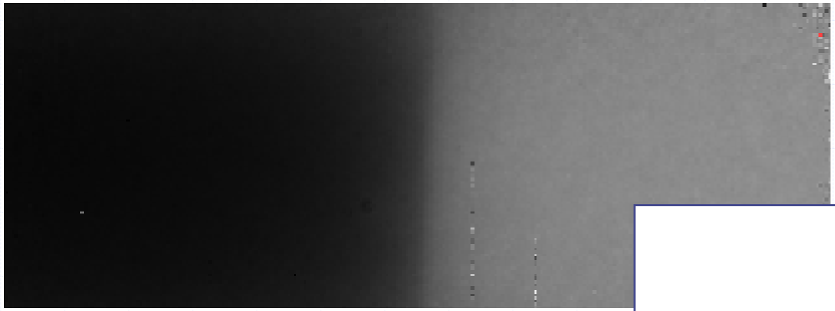


Single events (1ms)

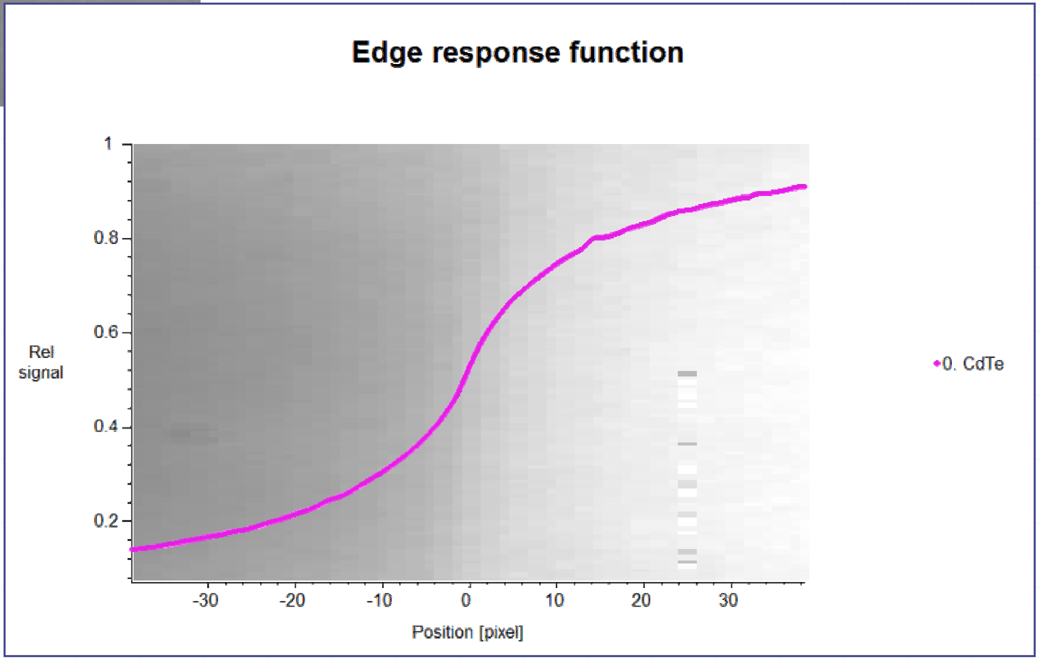
CdTe detector properties
Edge Response Function

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Projection of the straight edge of 1mm thick cadmium plate used.

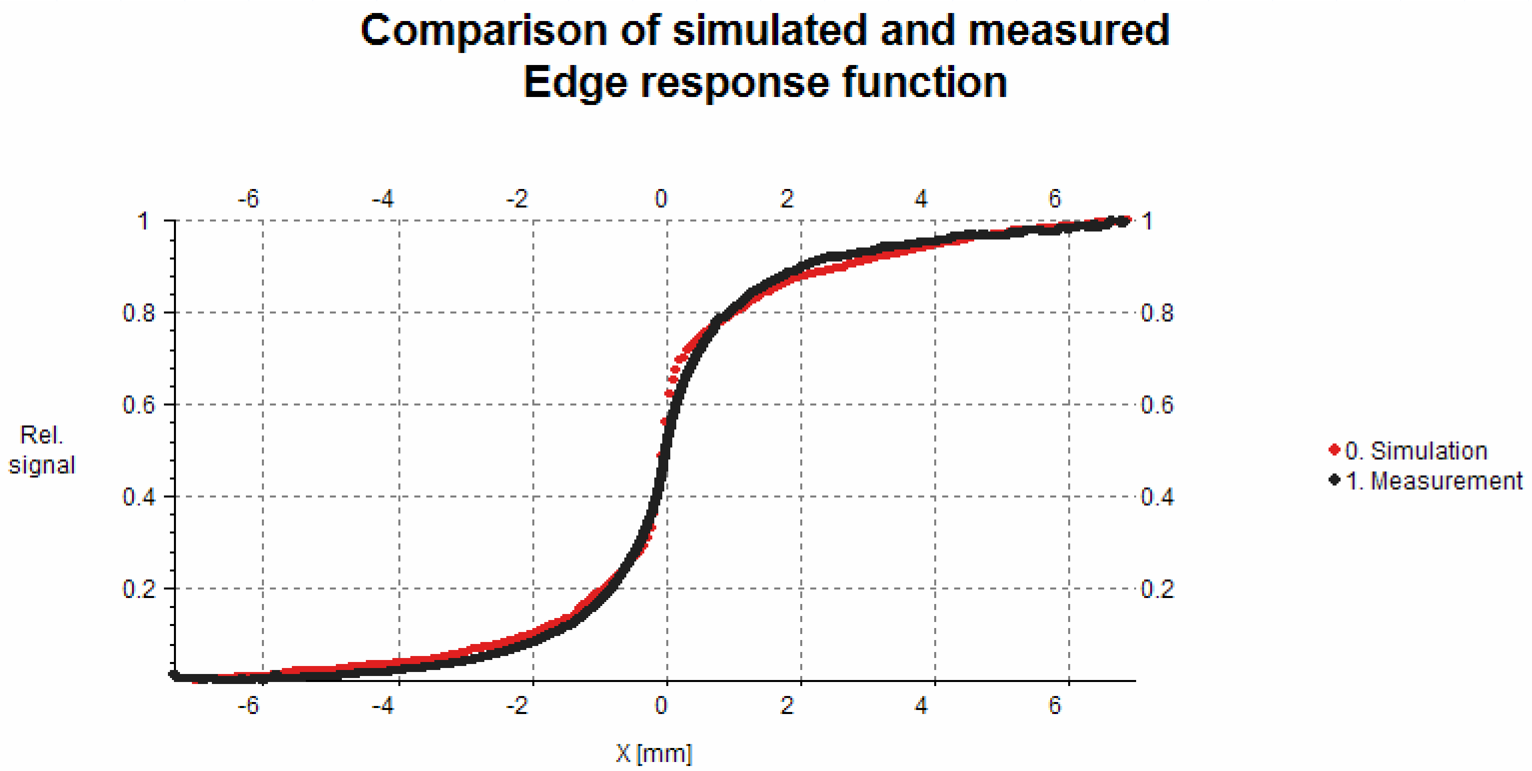


Flat Field correction by beam profile performed.



Comparison with simulation

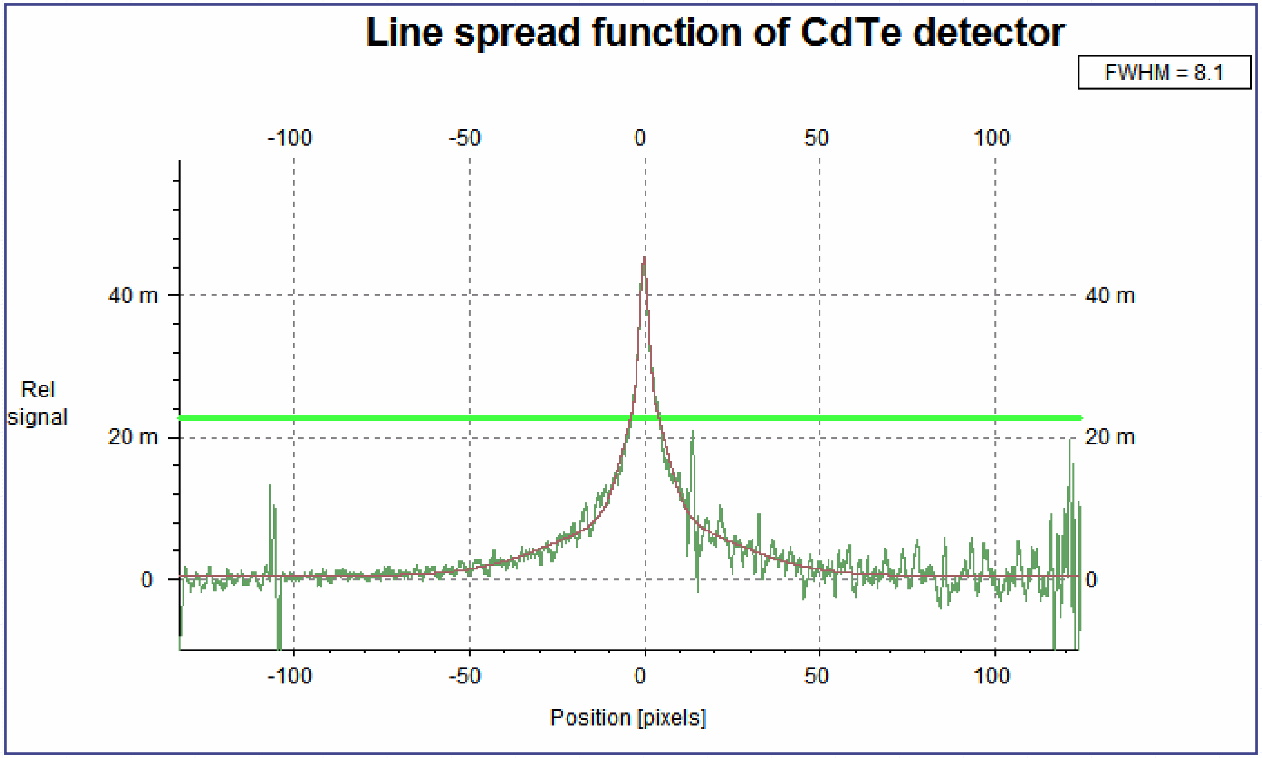
Institute of Experimental and Applied Physics
Czech Technical University in Prague



Institute of Experimental and Applied Physics
Czech Technical University in Prague

Real spatial resolution

LSF can be obtained by numerical differentiation of measured edge response function:

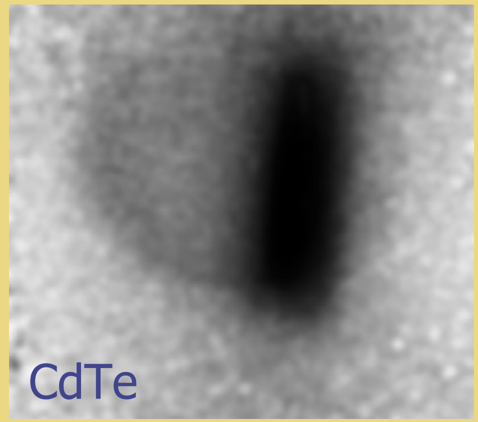


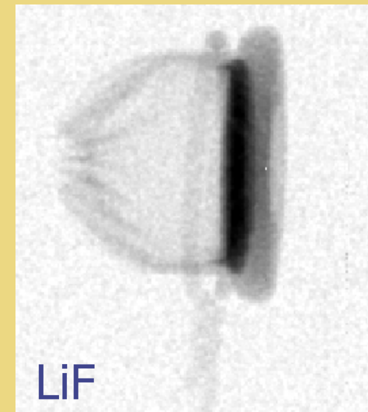
FWHM of LSF:
= 8.1 pixels
= 445 μm

Sample objects

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Blank cartridge





Head of fish

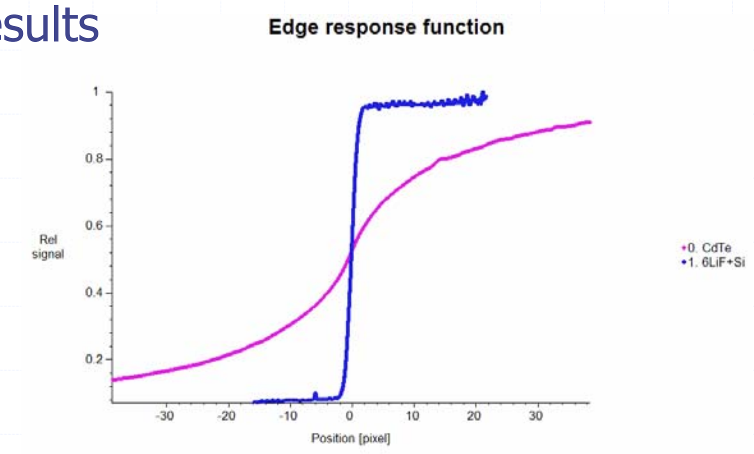
Comparison with other neutron converters

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Placement	Converter type	Spatial resolution	Detection efficiency	Remarks
Surface layer	^{6}LiF	100 μm	3 %	-
	^{10}B	50 μm	1.5 %	-
	^{113}Cd	1700 μm	5 %	-
	^{155,157}Gd	100 μm	Not tested	MC simulation, High background
Stuffed	^{6}LiF	~100 μm	40 %	MC simulation
Mixed	Cd in CdTe detector	445 μm	8 %	High background

Conclusions

- The simulations and measurements of CdTe sensor as neutron imager has been done.
- CdTe sensor in combination with Medipix2 chip can be used for direct neutron imaging but its imaging performance is not good. Particularly:
  - Spatial resolution is 450 μm
  - Detection efficiency is about 8%
- Other converter types can offer better results



Institute of Experimental and Applied Physics
Czech Technical University in Prague

Thanks a lot for your attention