PAUL SCHERRER INSTITUT

PSI

CCMX Competence Centre for Materials Science and Technology

IAEA International Atomic Energy Agency

Wir schaffen Wissen – heute für morgen

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Neutron Imaging Detectors

Outline

- A bit of history
- Present state-of-the-art detectors based on neutron sensitive scintillators and light-collection
- Scitnillators – a bit detailed look into them
- Alternative detector options
- Outlook

A bit of history

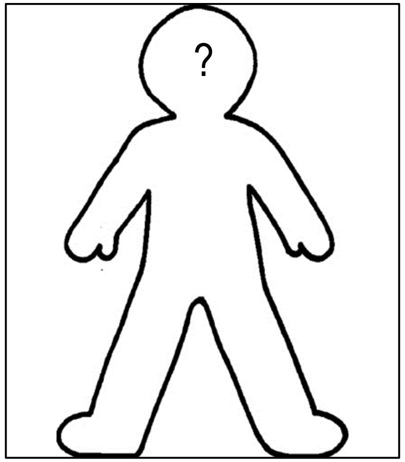
Have you ever seen a neutron?

- 1932 – Chadwick discovers the «HOLY» particle

- late 1938 – Kallmann & Kuhn take a first neutron image

[unpublished]

First neutron image to be found in literature



- Dec 1944 – Otto Peter

Neutronen-Durchleuchtung

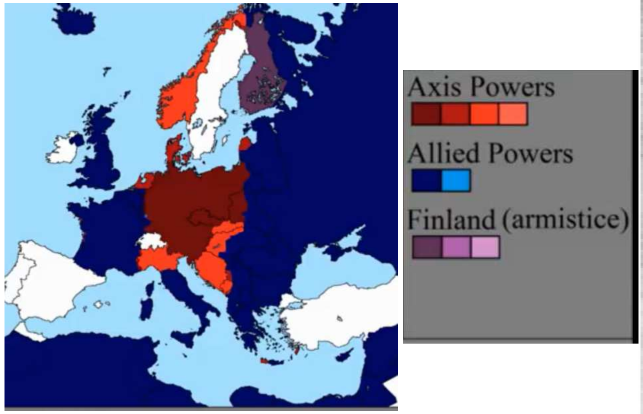
Von Otto Peter

Aus der Forschungsanstalt der Deutschen Reichspost, Berlin

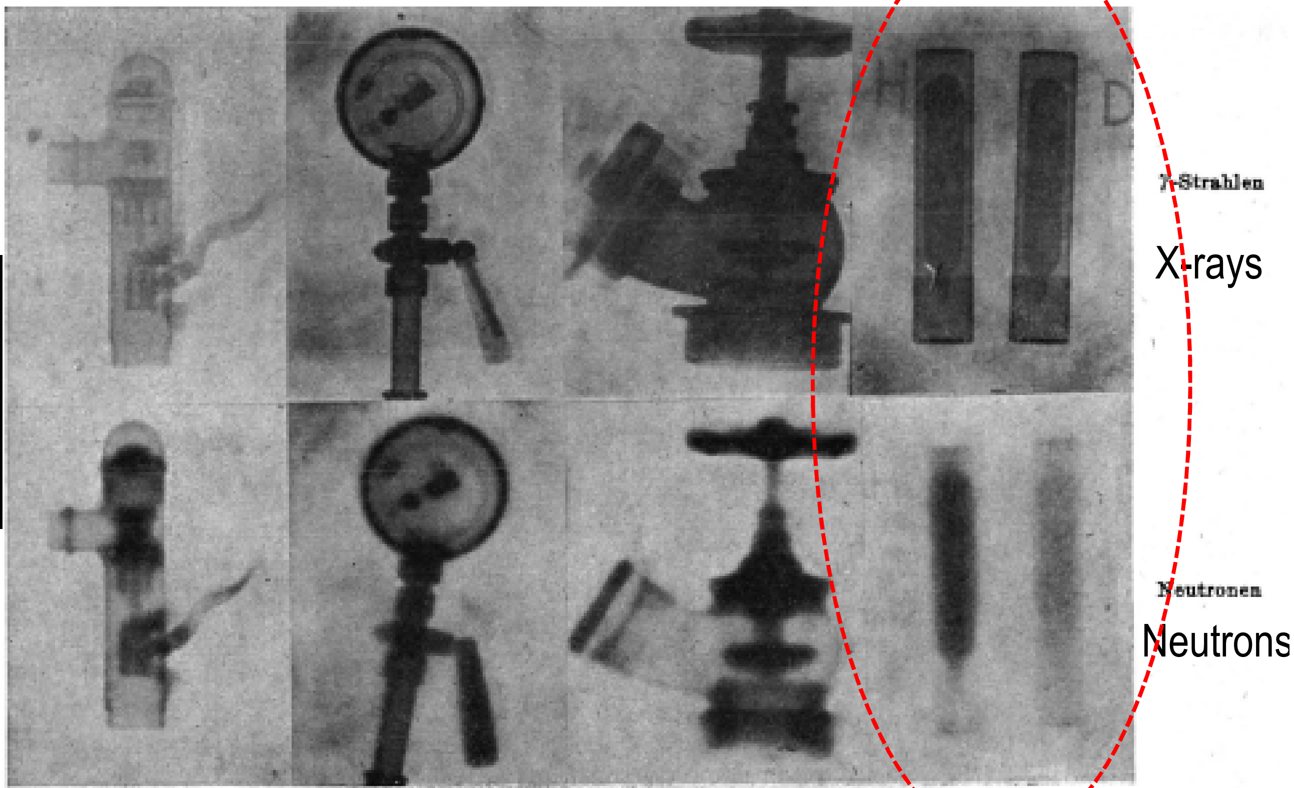
(Z. Naturforschg. 1, 557—559 [1946]; aus Rottweil a. N. eingegangen am 21. Juni 1946)

Erstmalig werden Durchleuchtungsaufnahmen mit langsamen Neutronen gemacht. Zur photographischen Wirksamkeit braucht man einen „Strahlenwandler". Die Bilder zeigen infolge der größeren Strahlenquelle nicht die Schärfe der γ-Strahl-Durchleuchtungen, erlauben jedoch neue Anwendungen.

Zeitschrift fuer Naturforschung (1946) 1, 557-559 http://zfn.mpdl.mpg.de/data/1/ZfN-1946-1-0557.pdf



https://www.youtube.com/watch?v=WOVEy1tC7nk



Definitions

Definitions defined by international standards

analog image

- an image produced by a continuously variable physical process (e. g. exposure of film)

autoradiograph

- an image of an object containing a radioelement obtained, on a recording medium, by means of its own radiation.

digital image

- an image composed of discrete pixels each of which is characterized by a digitally represented luminance level.

image processing

- a method whereby digital image data is transformed through mathematical function.

neutron radiography

- the process of producing a radiograph using neutrons as penetrating radiation.

neutron radiograph

- a permanent, visible image on a recording medium produced by neutrons passing through the material being tested.

neutron radiology

- the science and application of neutrons.

neutron tomography

- any neutron radiologic technique that provides an image of a selected plane in an object to the relative exclusion of structures that lie outside the plane of interest.

Other definitions

neutron imaging

- the term summarizes all advanced techniques using neutrons as a probe which are currently under development and not yet certified for industrial and commercial use.

From www.isnr.de (Intl Society for Neutron Radiography)

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History - Film

- Film + neutron-converter

+

A plate/layer converting neutron
to
a particle that blackens film
(Gd, Dy, In, Ag)

- Standardized technique
  - ASTM Standard Practice for Thermal Neutron Radiography of Materials (ASTM-E-748)
  -ASTM Standard Method for Determining Image Quality in Direct Thermal Neutron Radiographic Testing(CD II537)
- Application – used nuclear fuel rods *(www.inl.gov)*

Neutron detection process

- No direct excitation possible (missing charge of the neutron)

- Conversion process needed (capture, nuclear collision)

- Prominent converter materials: Gd, B-10, Li-6, He-3, U-235

- Secondary particles or radiation initiate light emission, charge transfer or other measurable excitation

Nuclear reactions for thermal neutron detection

$^{3}He + {}^{1}n \Rightarrow {}^{3}H + {}^{1}p + 0.77\ \text{MeV}$

$^{6}Li + {}^{1}n \Rightarrow {}^{3}H + {}^{4}He + 4.79\ \text{MeV}$

$^{10}B + {}^{1}n \Rightarrow {}^{7}Li + {}^{4}He + 2.78\ \text{MeV}$ (7%)

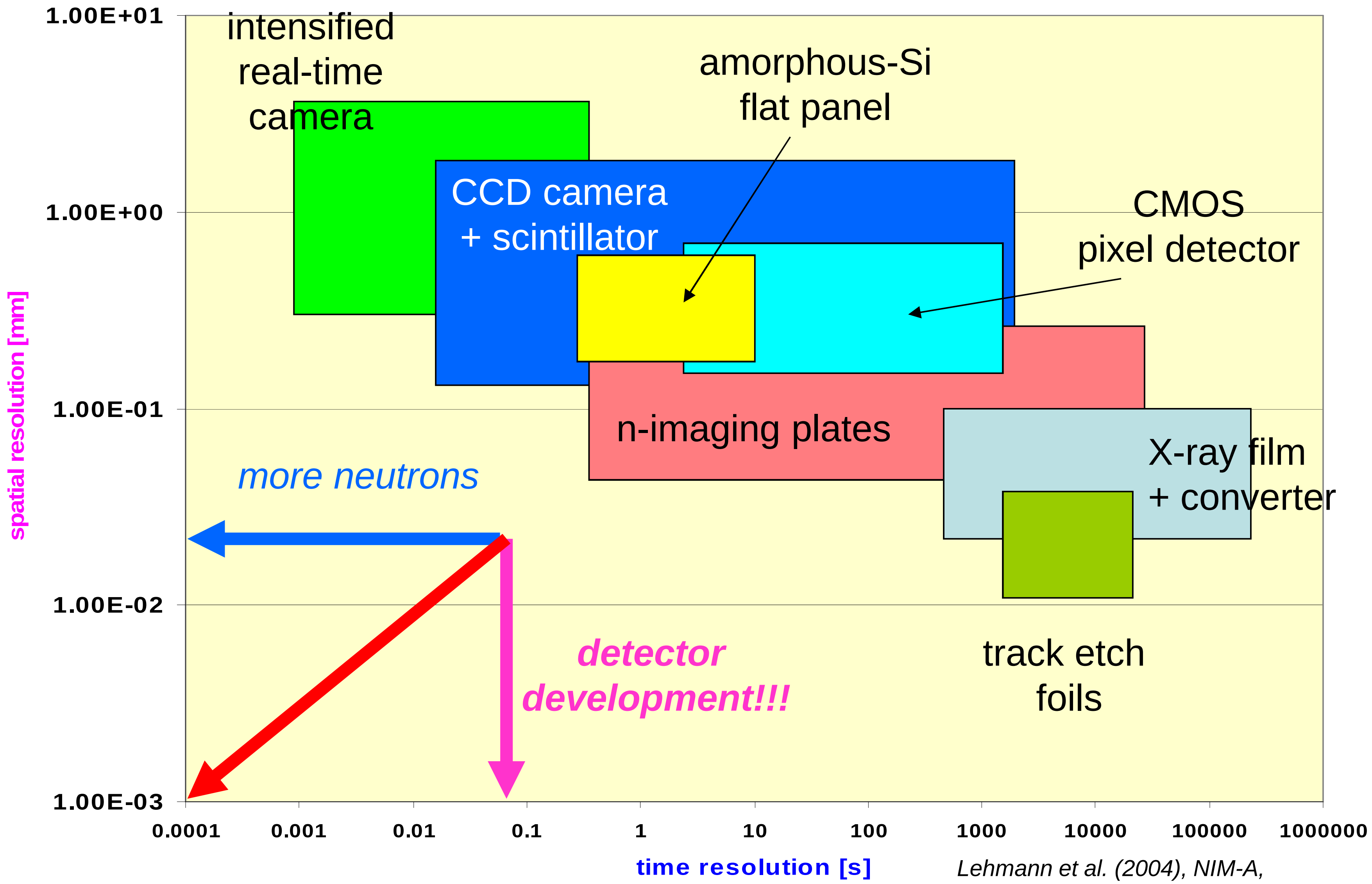
$\Rightarrow {}^{7}Li^{*} + {}^{4}He + 2.30\ \text{MeV}$ (93%)

$^{155}Gd + {}^{1}n \Rightarrow {}^{156}Gd + \gamma\ (7.9\ \text{MeV})$ + conversion electrons

$^{157}Gd + {}^{1}n \Rightarrow {}^{158}Gd + \gamma\ (8.5\ \text{MeV})$ + conversion electrons

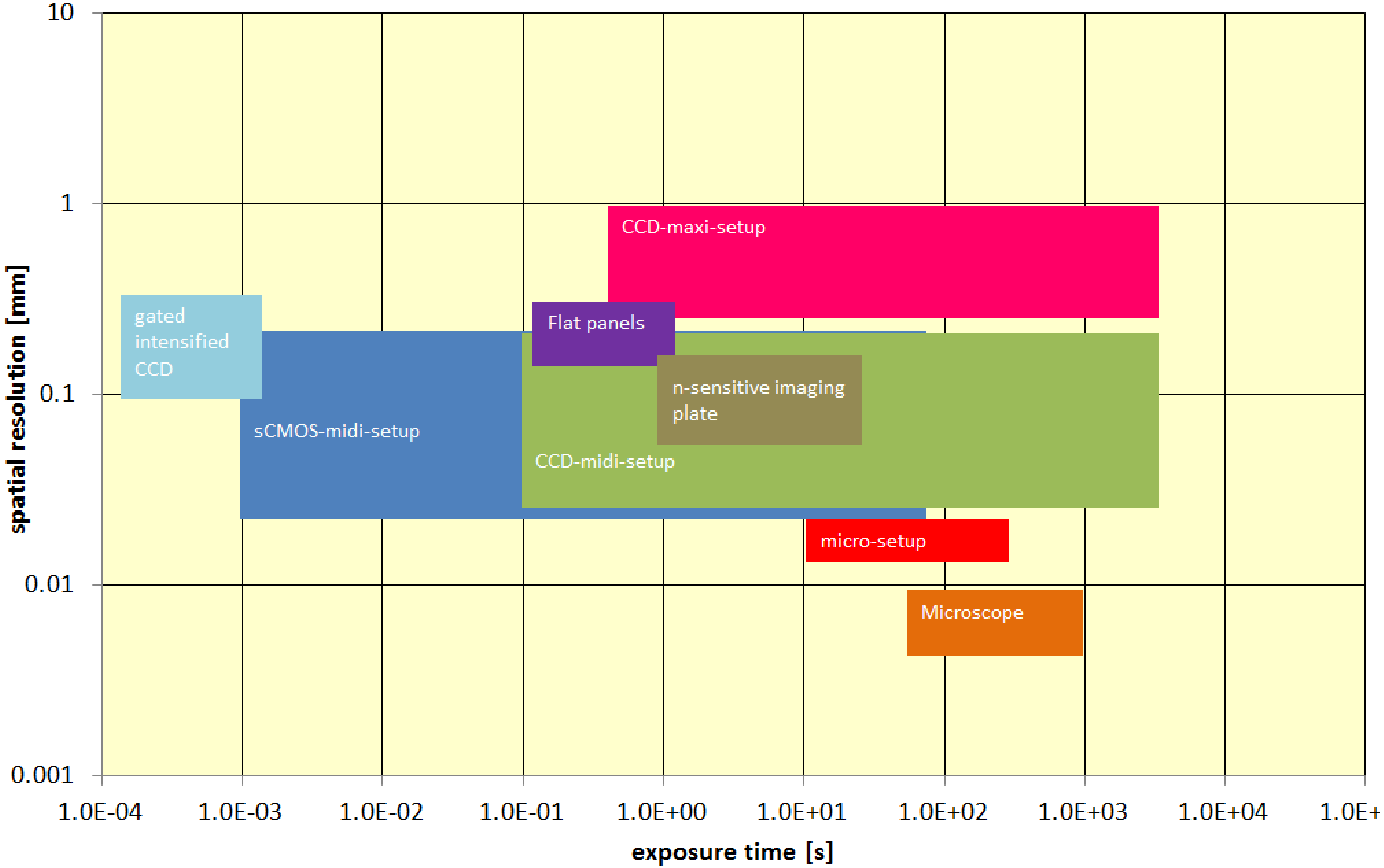
^{235}U, $^{239}Pu + {}^{1}n \Rightarrow$ fission products + 80 MeV

Neutron Imaging Devices – stand 2004



Lehmann et al. (2004), NIM-A,

Neutron Imaging Devices – stand 2015



Parameters of CCD cameras

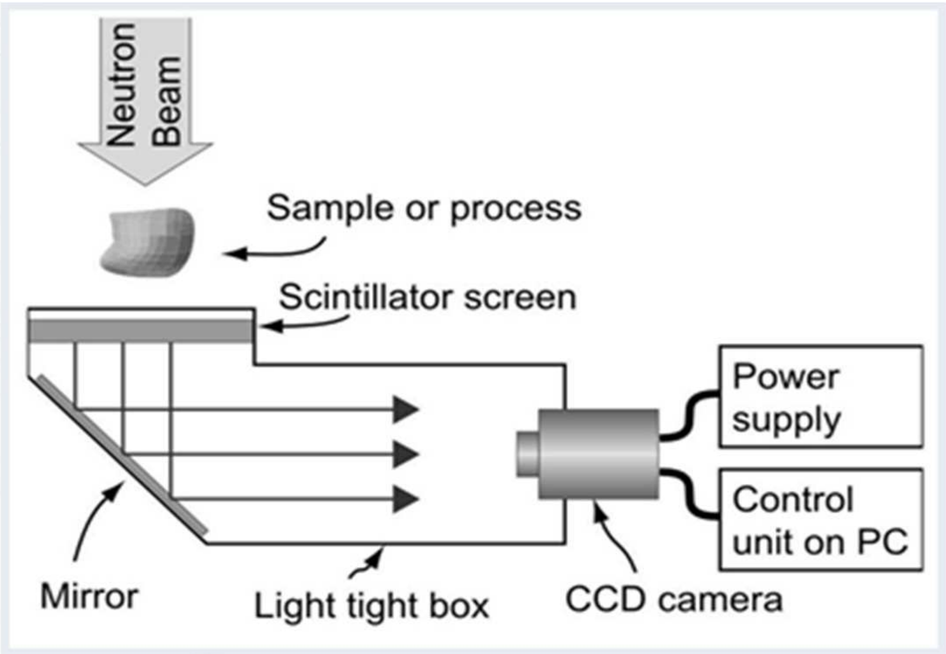
- Effective number of pixels – (e.g. 2048 x 2048, even 16k x 16k exist)
- Pixel size – can go down to few micrometres (4.0 µm)
- Chip size – pixel size times effective number of pixels
- Dark current noise – created from the thermal energy within silicon lattices comprising the CCD (as low as 0.01 e^-/s) => That's why we cool the chip☺
- Readout noise – e.g. 1.6 e^- (either rms or median value)
- Total noise – sqrt(readout noise^2 + dark noise^2)
- Full well capacity – largest charge a pixel can hold before saturation (e.g. 30'000 e^-)
- Dynamic range – ability of a camera to record simultaneously very low light signals alongside bright signals (Full well capacity/mean readout noise) e.g 18'000:1
- A/D converter – 8 bit, 12 bit, 16 bit
- Temporal resolution – CCD down to 10 µm regime up to 100s seconds
- Quantum efficiency – incident photon to converted electron ratio
- Operating conditions, (temperature, triggers, interfaces)

Neutron or photon/electron statistics?

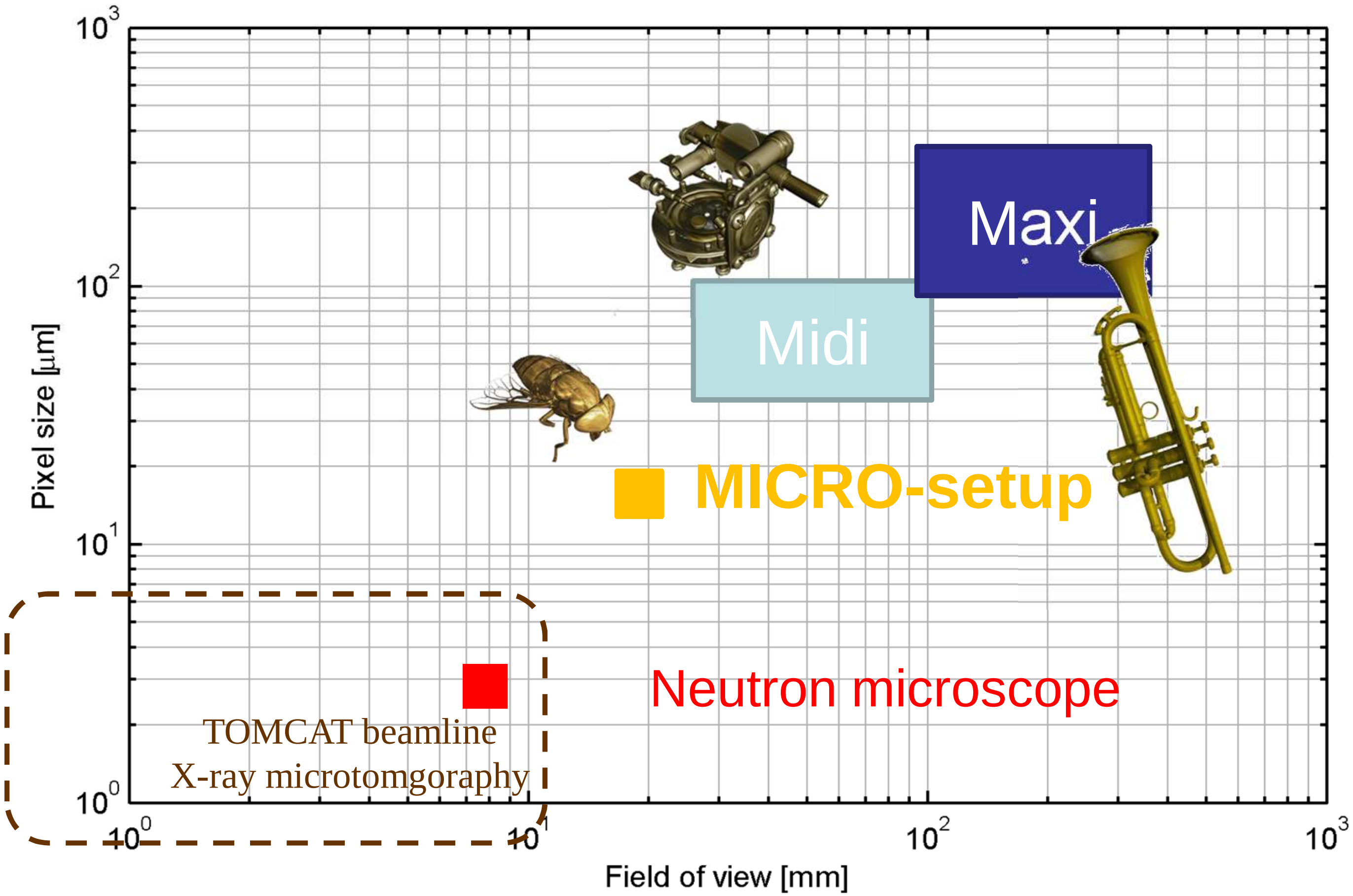
- It is important to realize what is the limiting factor of your CCD-scintillator set up?

Number of counts detected by one pixel
Vs.
Number of neutrons detected by the scintillator area corresponding to one pixel

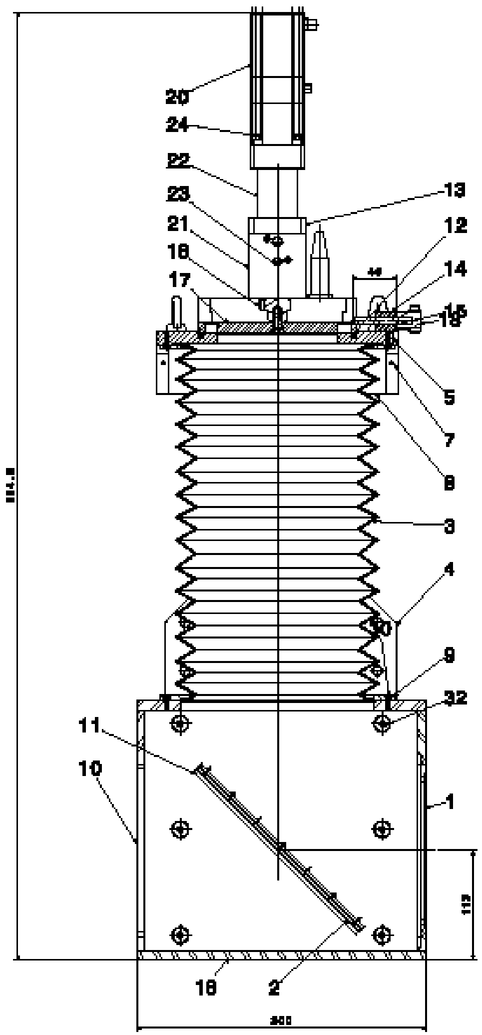
> 1

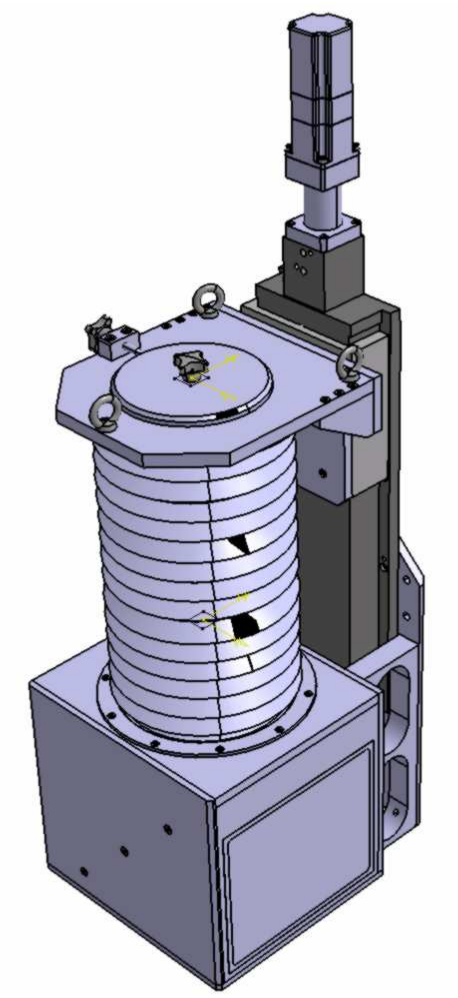


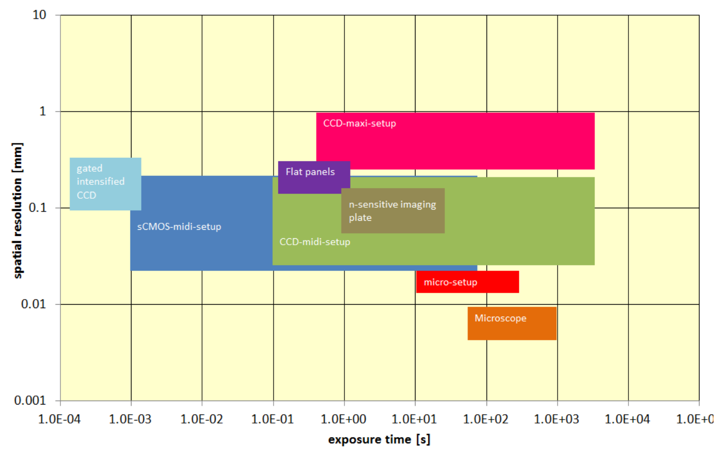
FOV and pixel size for the CCD/sCMOS detector systems at PSI's NI facilities



CCD-detector MIDI (middle positions)

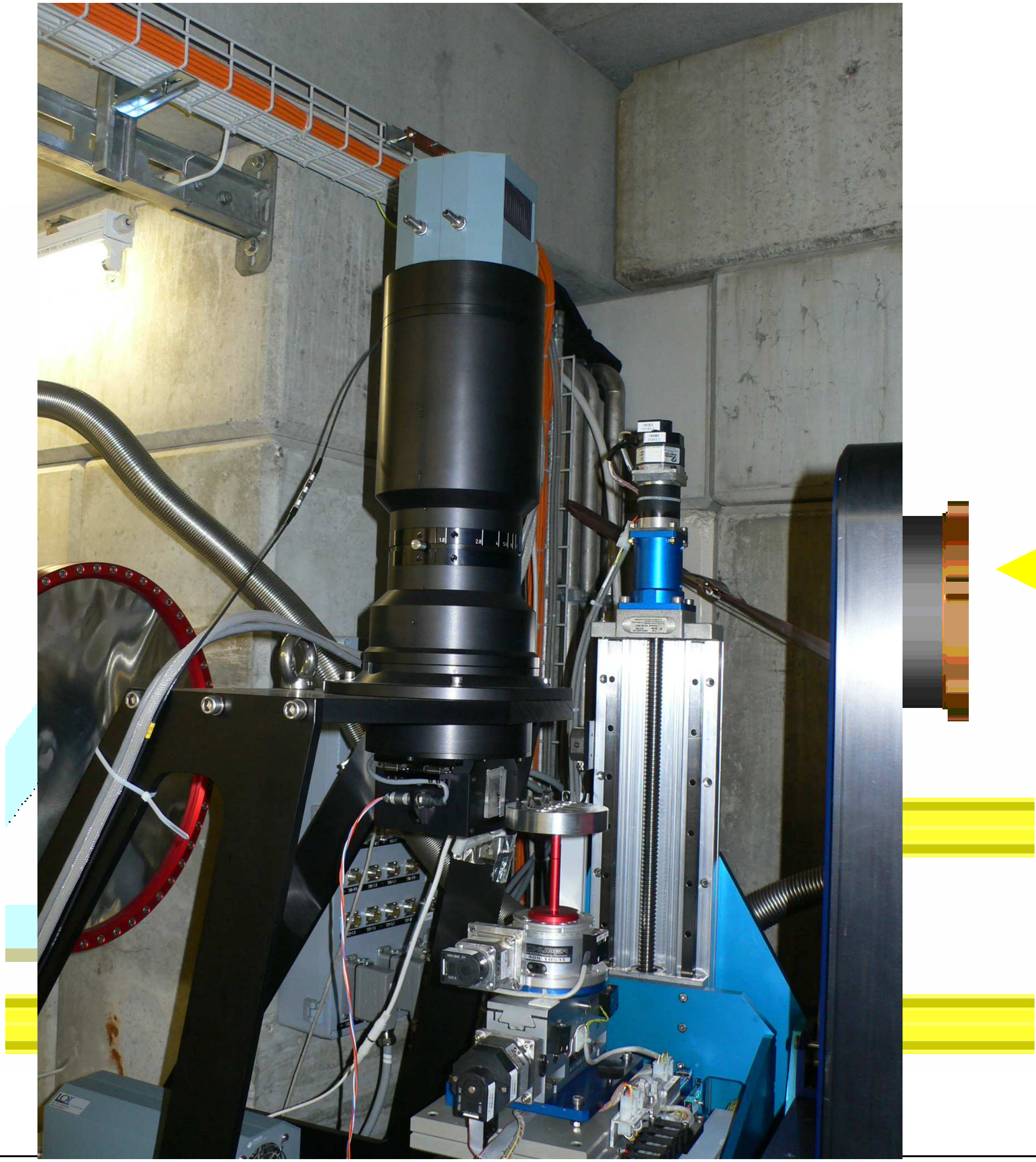




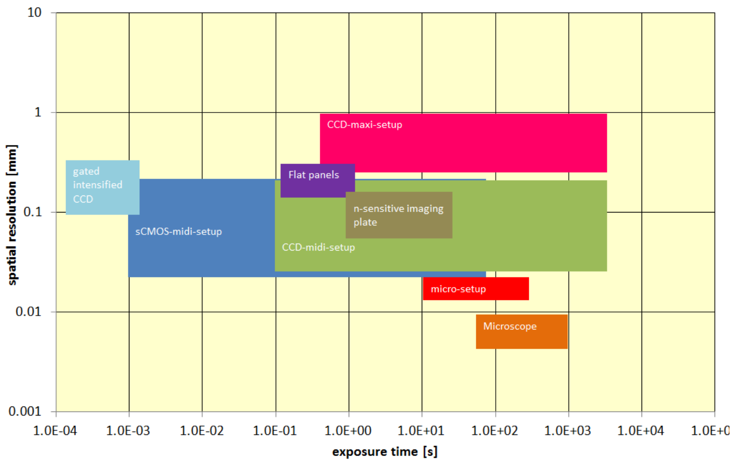


FOV between 15 and 3 cm

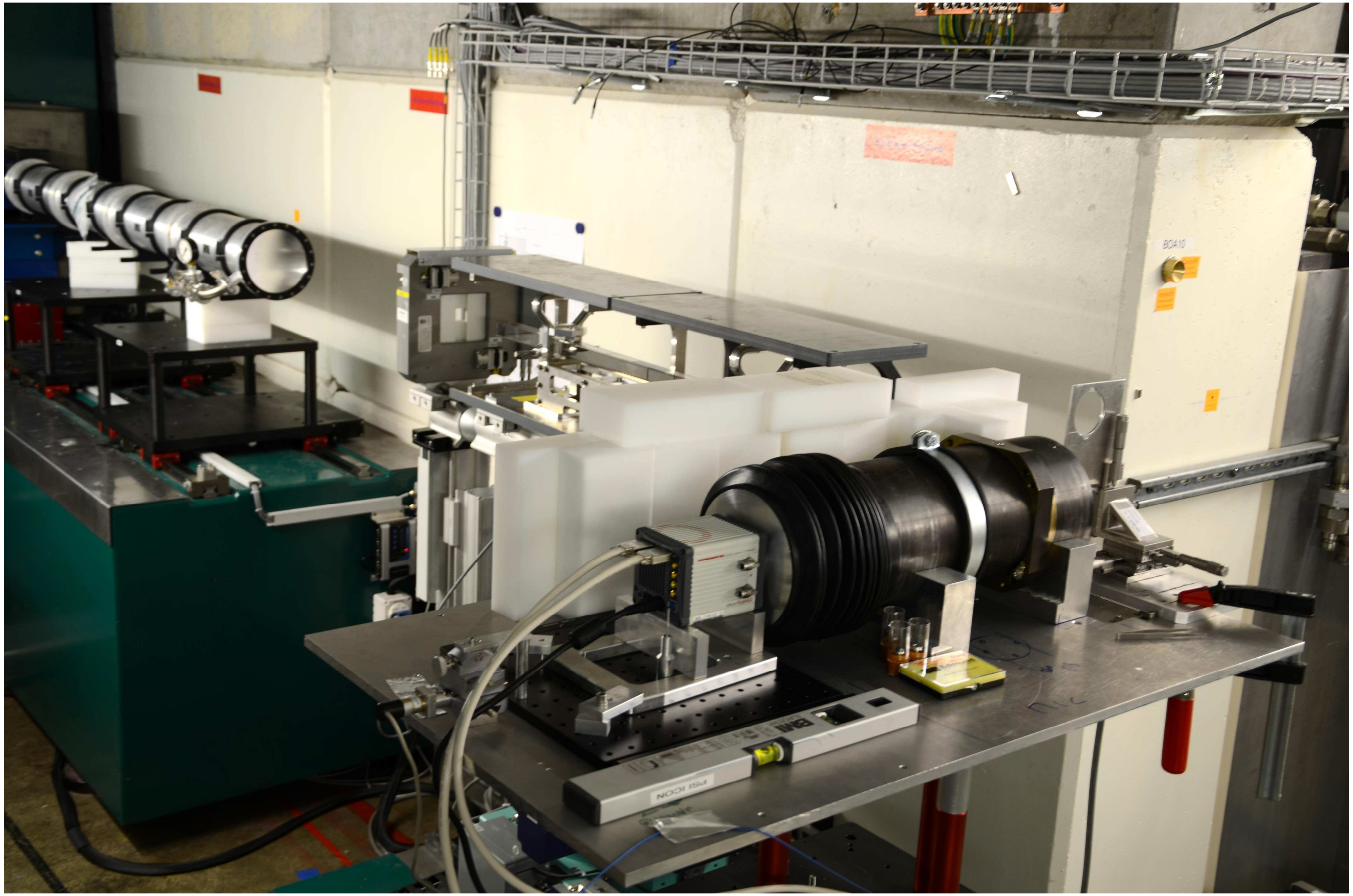
Micro-Tomography-Setup @ ICON



- FOV: 27mm x 27mm
- Pixel size: 13.5µm
- CCD with 2048*2048 pixels
- Scintillator 10 µm thick
- L/D>1000

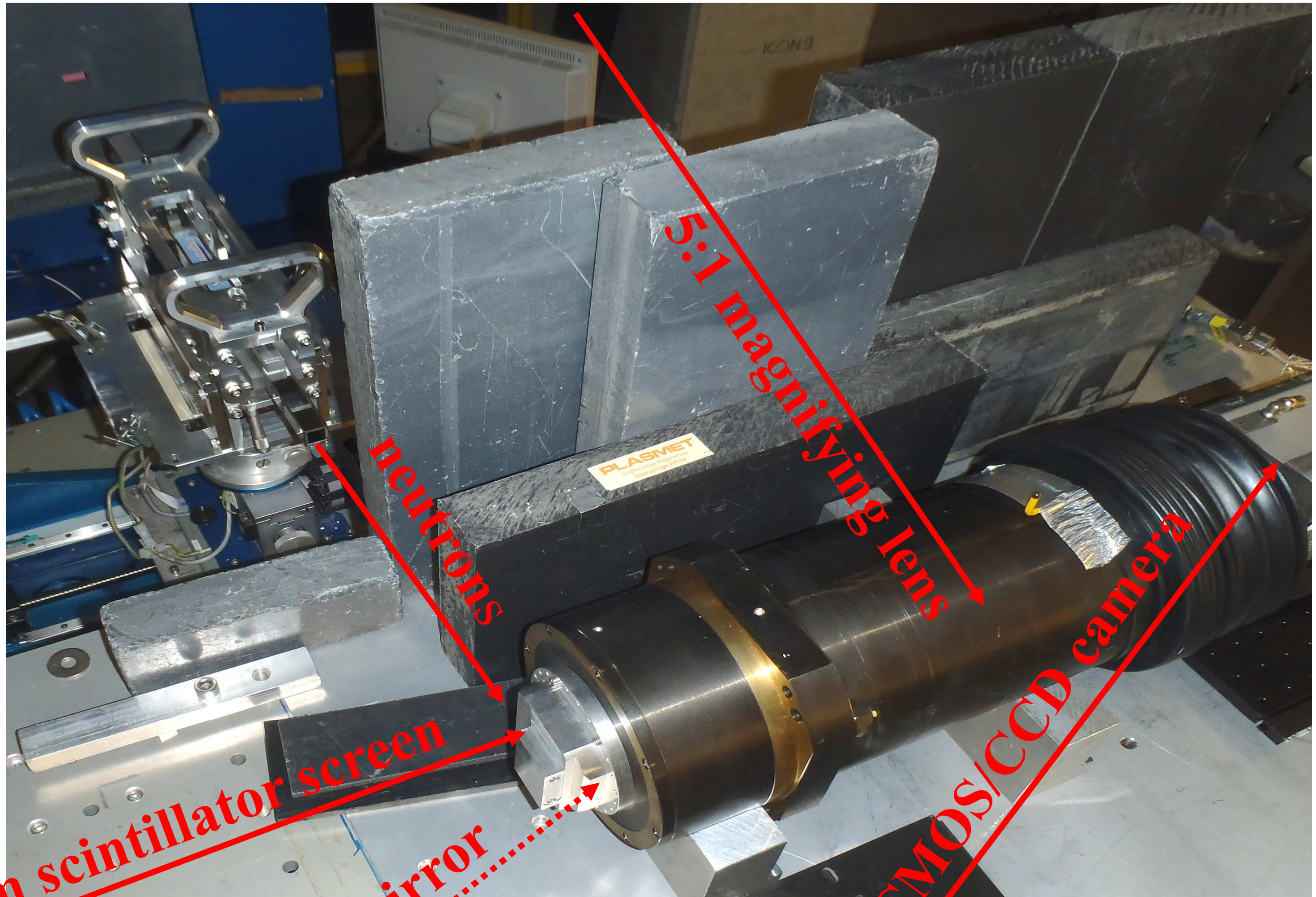


Neutron microscope – prototype 1.01



Trtik et al. Physics Procedia (2015) Neutron Microscope prototype 1.01 at BOA beamline

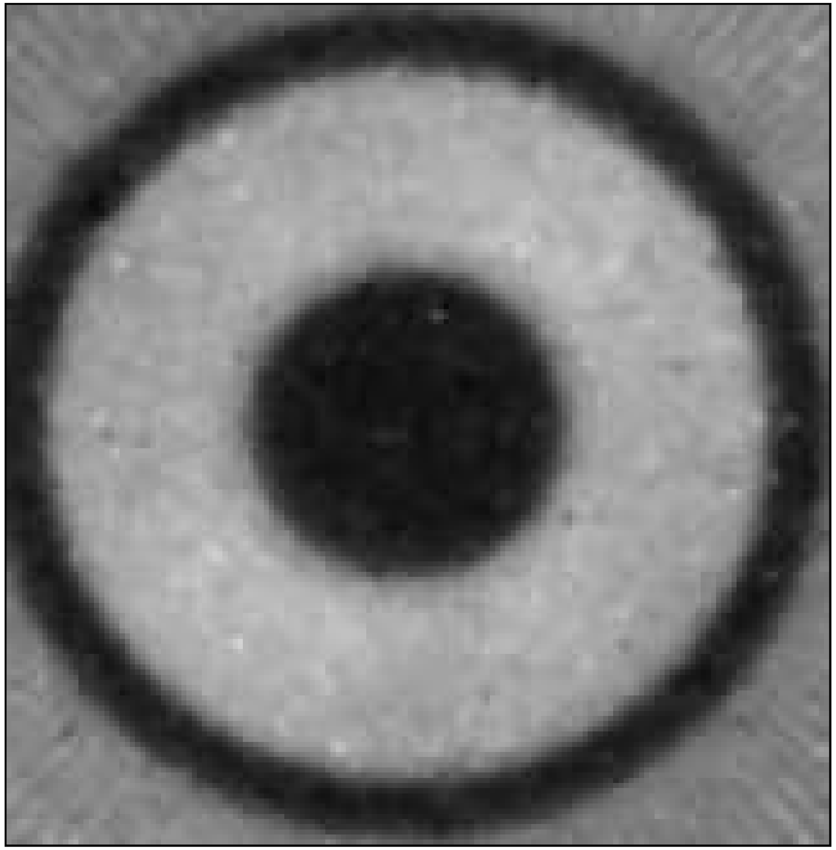
Neutron microscope – prototype 1.01



P. Trtik, et al., Physica Procedia (2015)

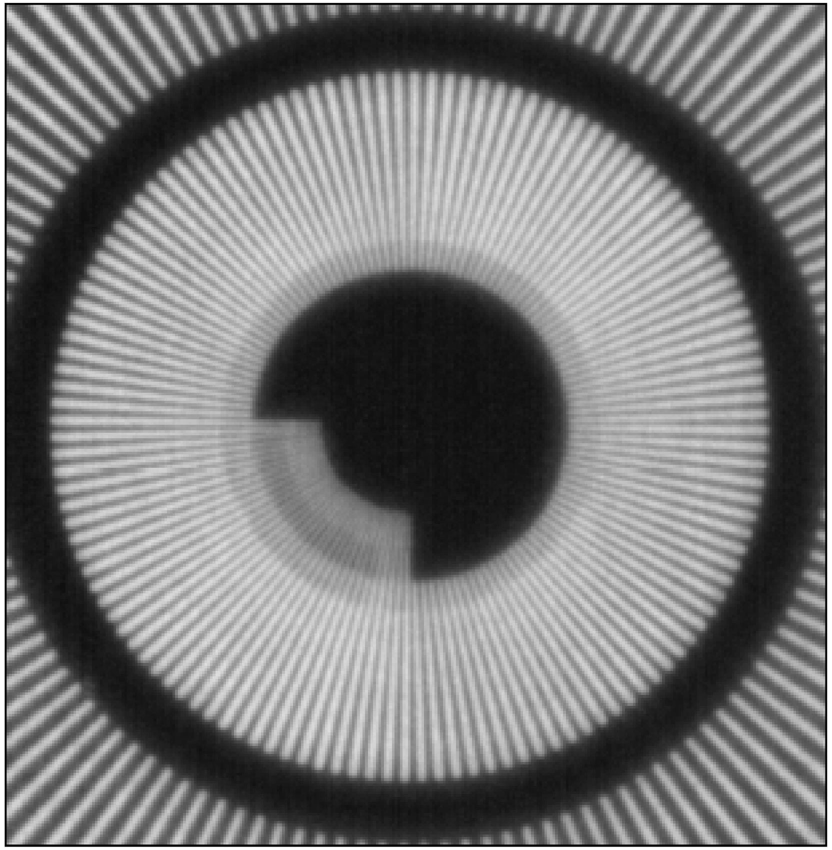
MICRO-setup vs Neutron Microscope

MICRO-setup



2 mm

Neutron Microscope



2 mm

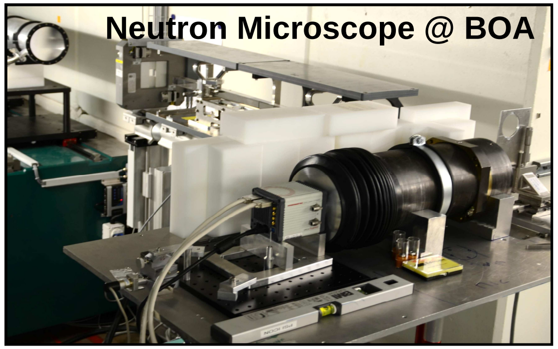
Users ?☺

Neutron Microscope Prototype 1.01

Neutron Microscope

Design and optimization of:

- Tailored magnifying optics
- High-resolution high-performance scintillators
- High-resolution high-sensitivity camera
- Tailored neutron optics for (2D samples)
- Neutron collimator on the basis of MCPs
- High-precision sample positioning stage
- Neutron-sensitive resolution test objects

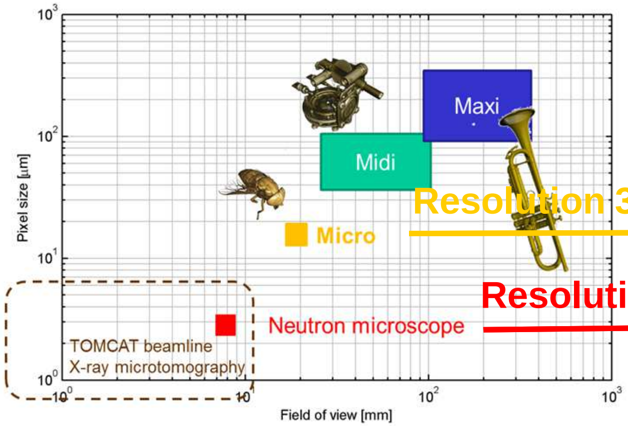


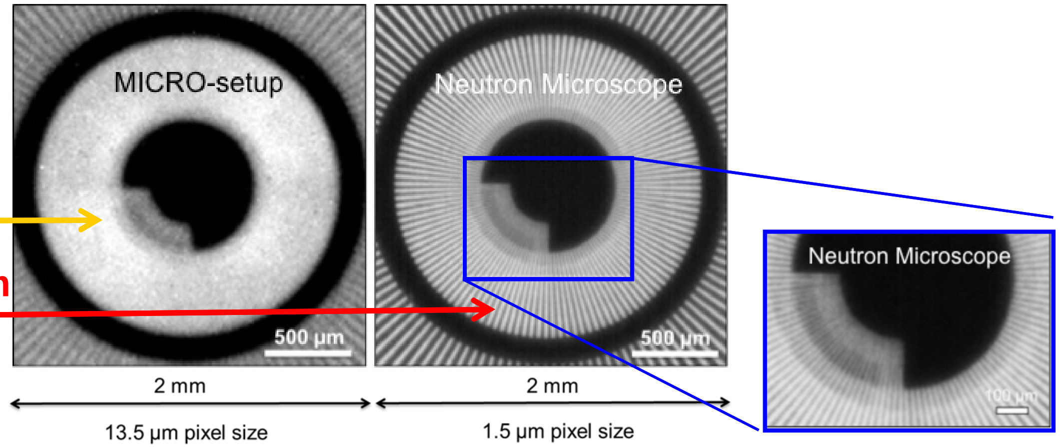
Applications

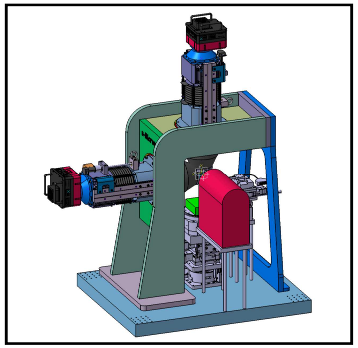
Current frontiers of neutron imaging:

- Fuel Cell research
- Battery research and development
- Material failure and defect analysis
- Liquid transport in porous media
- Nuclear safety materials research
- Any other we are not aware of yet

All enjoying complementarity of neutrons and X-rays







Design of final instrument

- to be installed on ICON and BOA
- user operation from 2016/17
- target resolution below 5 **µm**

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

CCMX
Competence Centre for Materials Science and Technology

PSI-CROSS

- *P. Trtik and E.H. Lehmann, NIM-A (2015)*
- *P. Trtik, et al., Physics Procedia (2015)*

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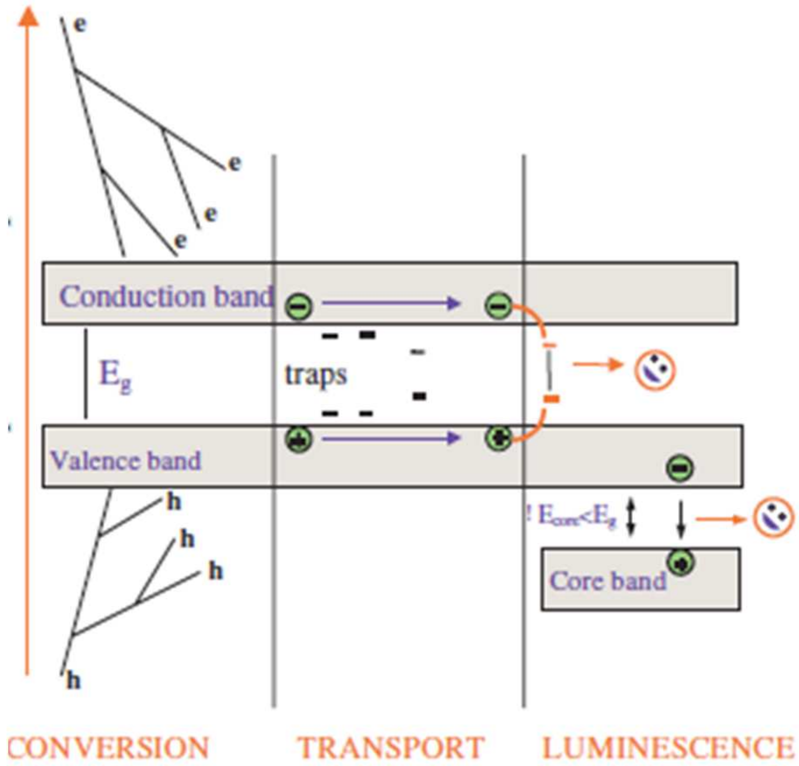
Scintillation principle

- High energy radiation creates free electrons and holes
- Holes convert to the top of the valence band and highly excited electrons convert (inelastic- / elastic scattering, etc.) to the bottom level of the conduction band
- The so-called thermalized electrons and holes can be captured by different traps (defects etc).).
- By recombination of the thermalized electrons and holes part of the energy is transferred to the emission center and lead to the observed luminescence.
- The fluorescence intensity of a phosphor is furthermore dependent from several factors:
  - Energy levels of the emitting ion in the crystal structure
  - Crystal structure (disorder, inhomogeneity, …)
  - Purity of the phosphor (impurities)



Nikl, J o Luminescence (2006) review of X-ray scintillators

Slide courtesy of Walfort (RC TRITEC) et al., WCNR-10, (2014)

Relevant properties of scintillator screens

- Efficiency of the neutron capture (neutron stopping power)
- Light yield per neutron (ph/n)
- Emission spectrum
- Rise time, decay time and afterglow (persistance)
- Long-term stability of the above properties (degradation mainly due to radiation)
- Other relevant properties (stability in various environments, e.g. hygroscopicity)

Relevant properties of scintillator screens

- Efficiency of the neutron capture (neutron stopping power)

  - thickness (the thicker screen, the larger stopping power)

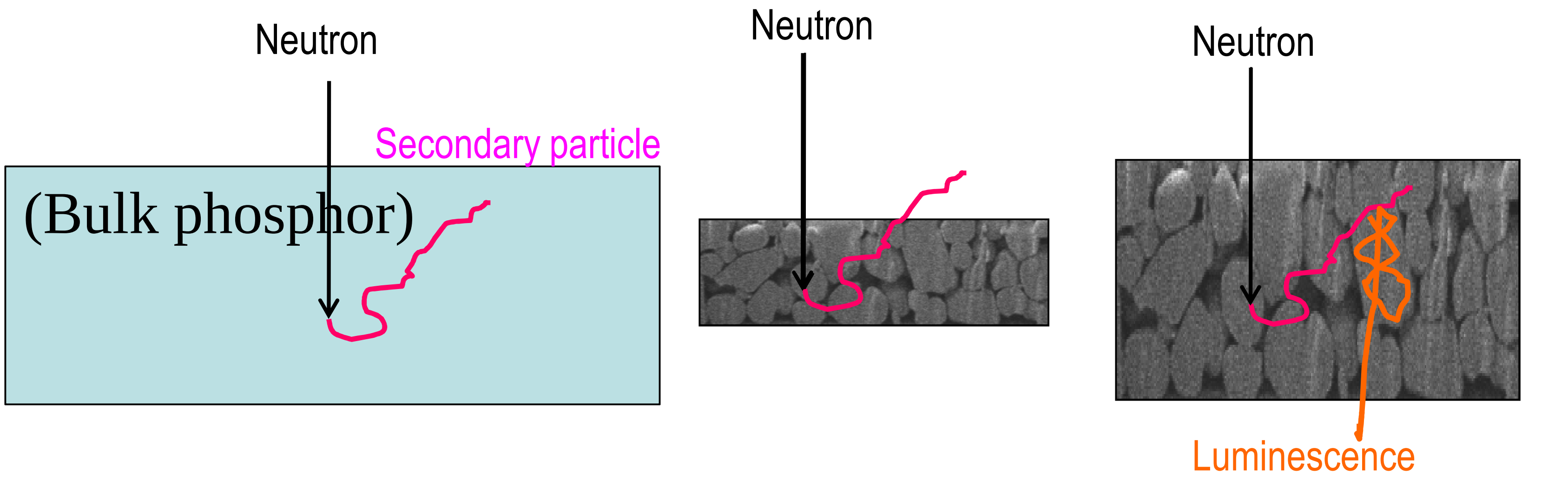
  - Cross-section (the larger the cross-section, the larger the stopping power)

Relevant properties of scintillator screens

- Efficiency of the neutron capture (neutron stopping power)
- Light yield per neutron (ph/n)

  - intrinsic number for the bulk material (e.g. for ZnS:Ag = 160'000 ph/n)

  - in reality, it is a function of thickness of the screen, microstructure of the scintillator screen, phosphor material properties (e.g emission spectrum, refractive index)



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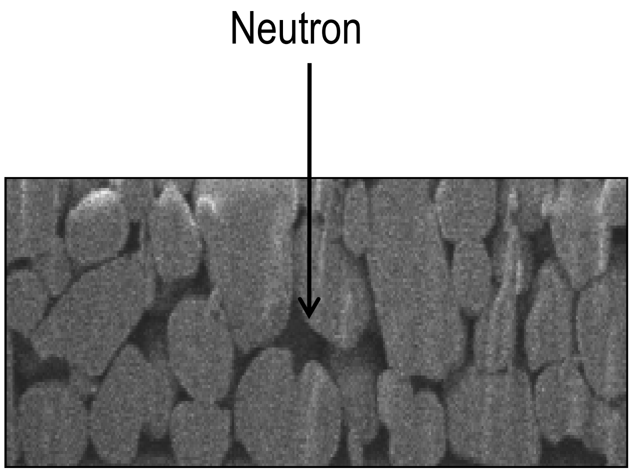
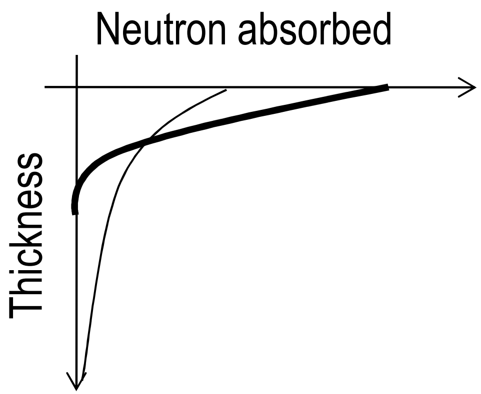
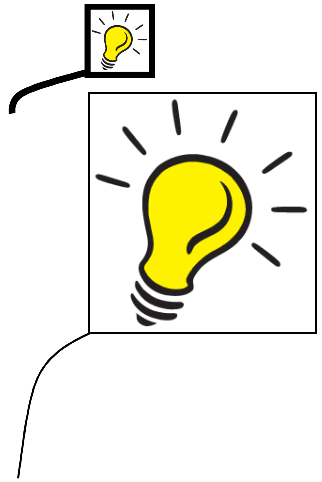


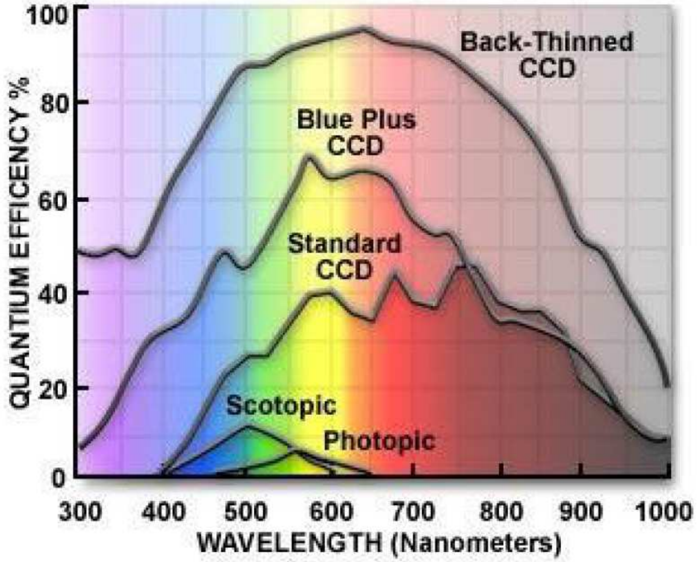


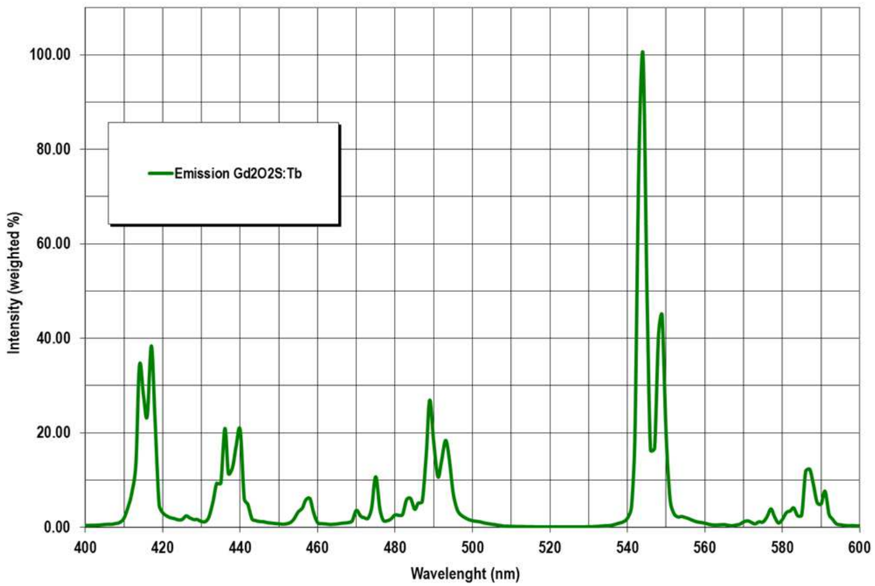


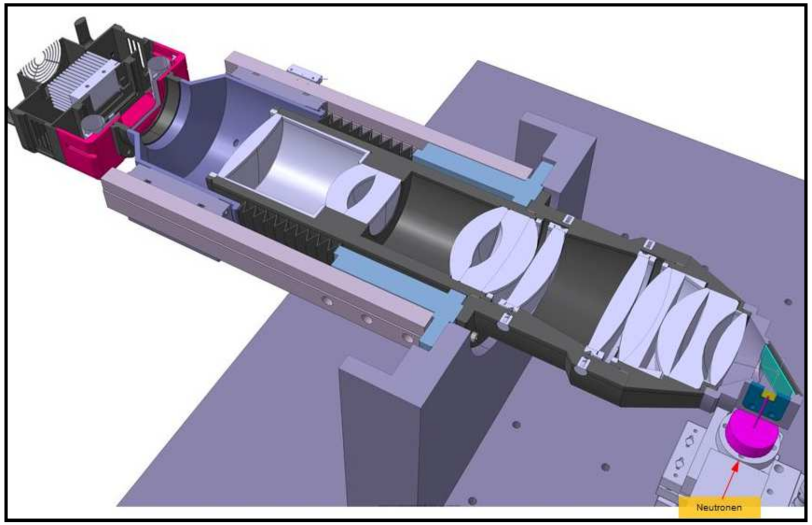
Self-shielding!

Relevant properties of scintillator screens

- Efficiency of the neutron capture (neutron stopping power)
- Light yield per neutron (ph/n)
- Emission spectrum







THE EMISSION SPECTRUM IS CRUCIAL FOR
(i) EFFICIENCY OF CCD
(ii)DESIGN OF THE OPTICS

Relevant properties of scintillator screens

- Efficiency of the neutron capture (neutron stopping power)
- Light yield per neutron (ph/n)
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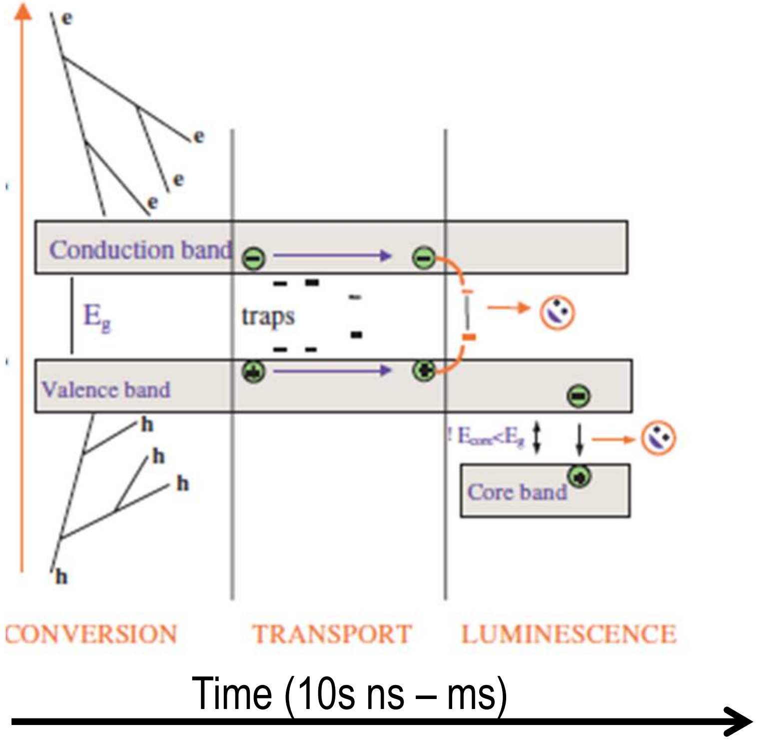
- Rise time, Decay time and afterglow (persistance)



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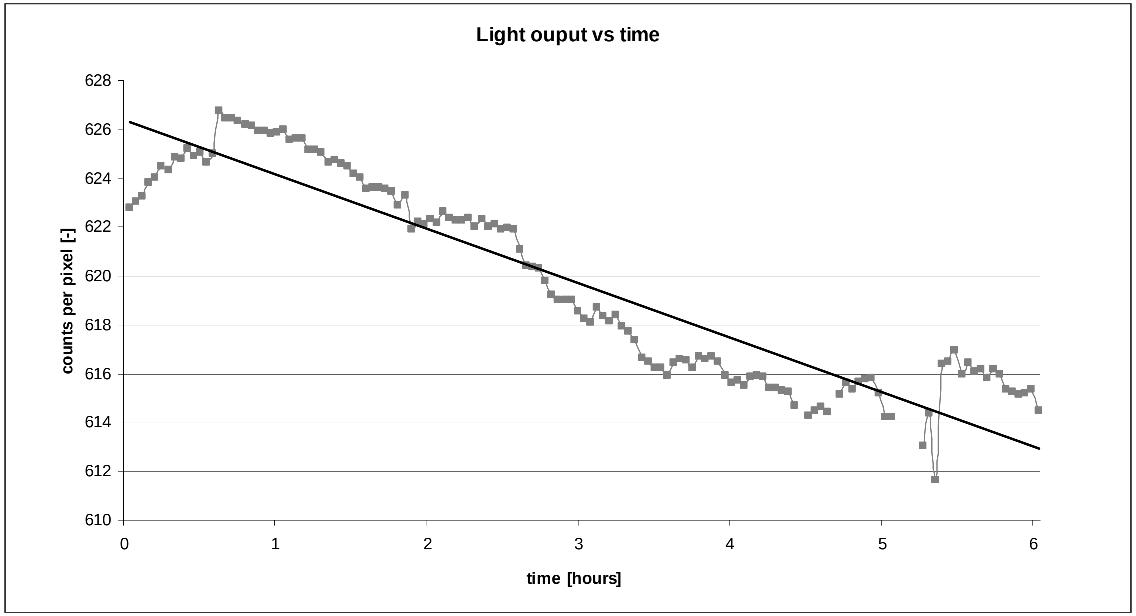

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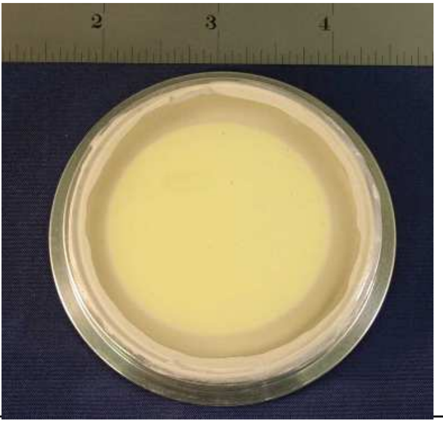
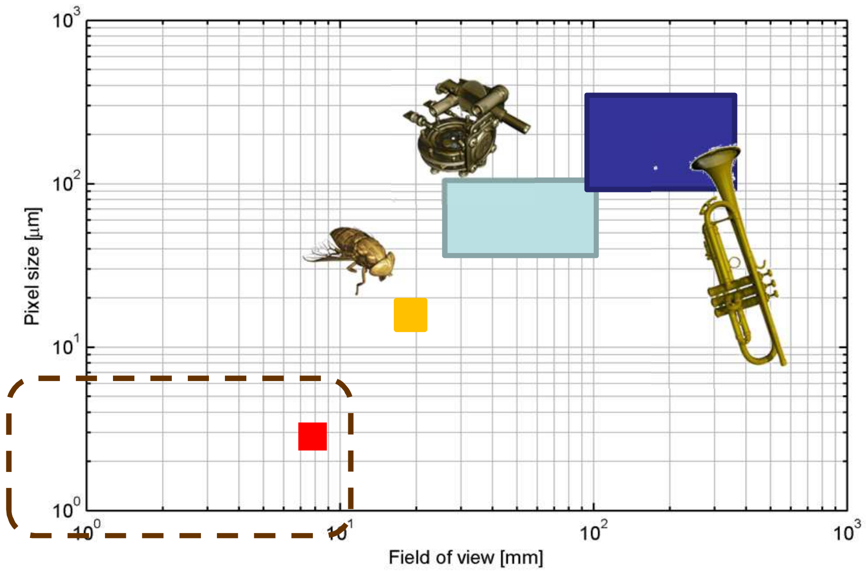
GdI_3:Ce



MUST BE STORED IN SEALED CONDITION

Neutron-sensitive scintillators

- Neutron scintillators convert neutrons to visible light
- There are two commonly used materials for neutron-senistive scintillatoin
- ^{6}LiF/ZnS:(dopant e.g Ag)
- Gd_2O_2S:(dopant e.g. Tb)



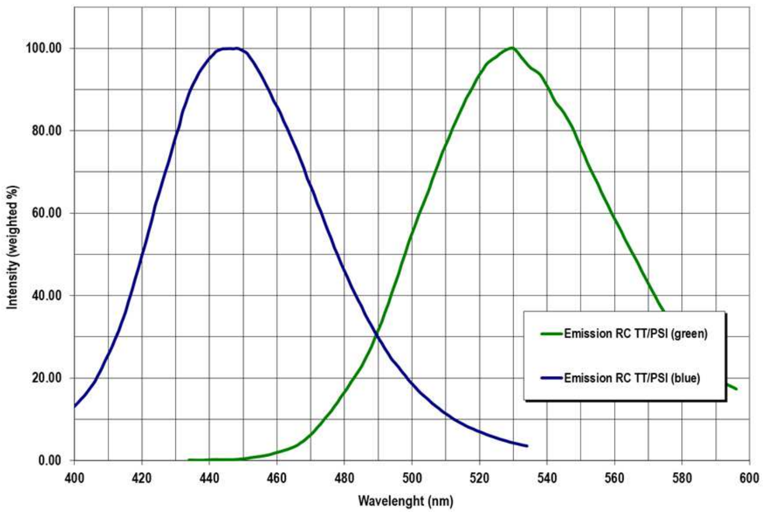
^{6}LiF/ZnS:(dopant e.g. Ag, Cu)

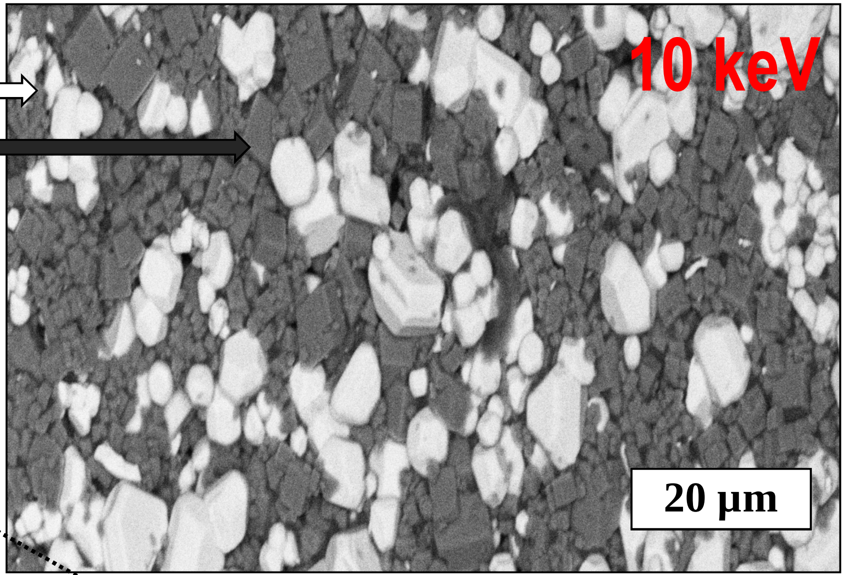
- Two (three) components scintillator

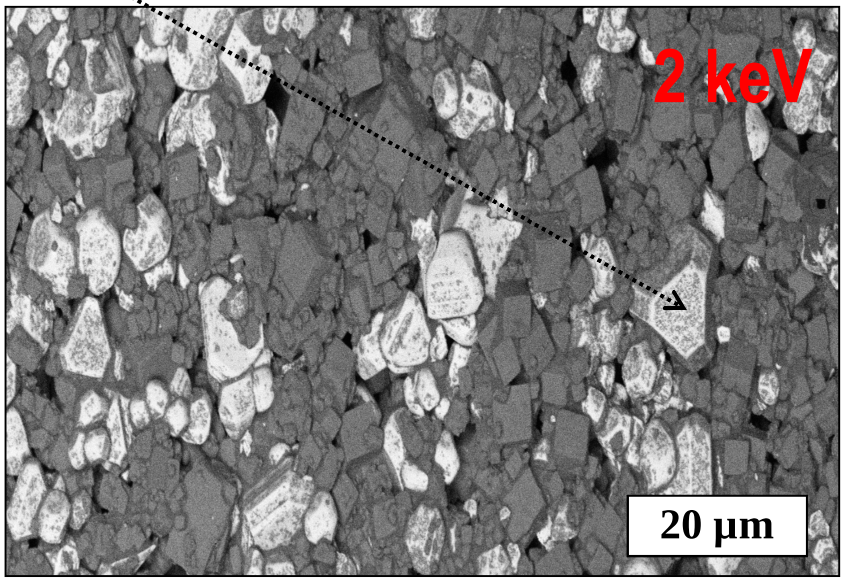
- neutron absorber (^{6}**Li**F)
- light emitter
- (in/organic binder)

^{6}Li + n ⇨ ^{3}H (2.73 MeV) + ^{4}He (2.05 MeV)

- Relatively low neutron capture efficiency
- Very high light output (for Ag doped material 160’000 ph/n)
- The range of ^{3}H (2.73 MeV) ~10s µm
- The range of ^{4}He (2.05 MeV) ~ up to 10 µm

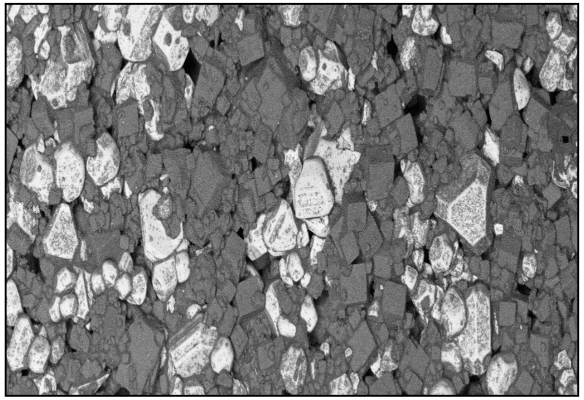


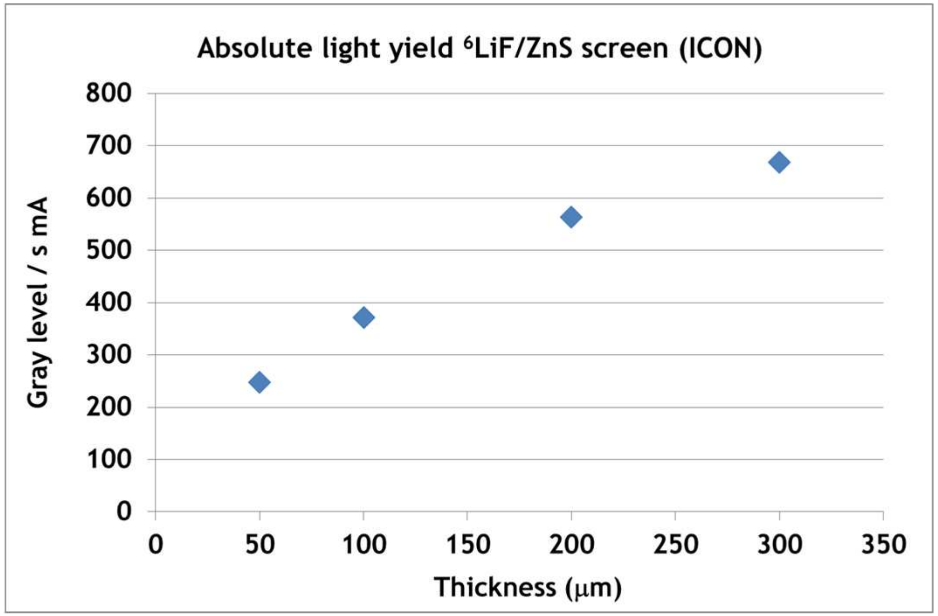


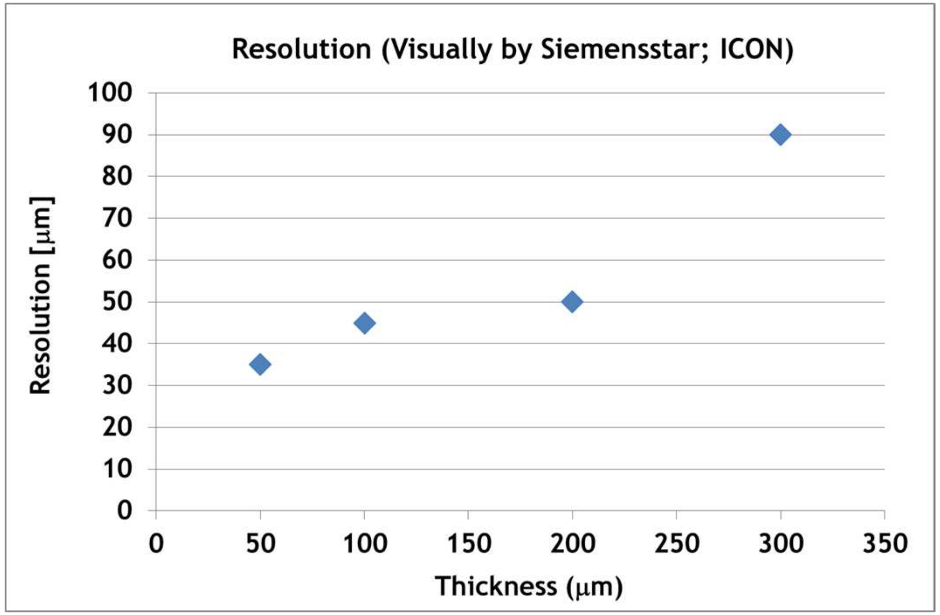


^{6}LiF/ZnS:(dopant e.g. Ag, Cu)

- Light-output-optimized ratio of LiF to ZnS is 1:2
- The smaller thickness, the higher resolution
- The larger thickness, the higher light-output
- Self-shielding (saturation of light output) from about 400 µm





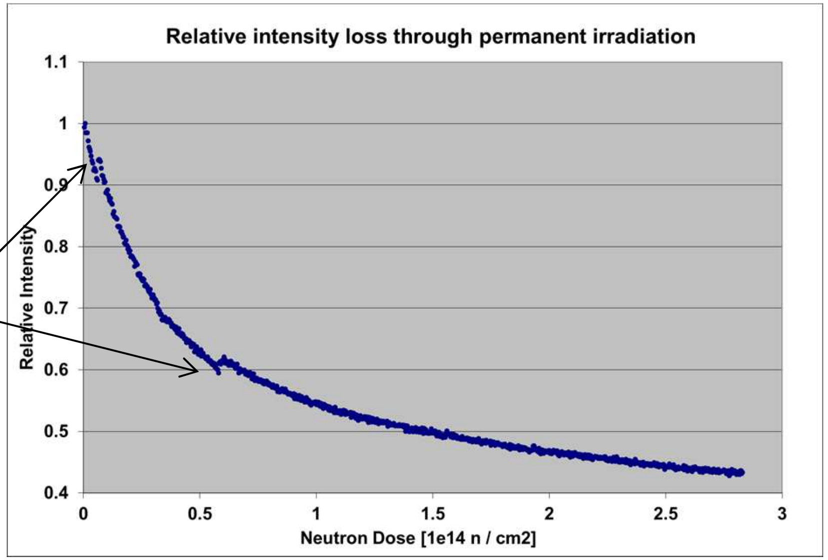


Walfort, Gruenzweig, Trtik, Hovind, Lehmann, WCNR-10 (2014)

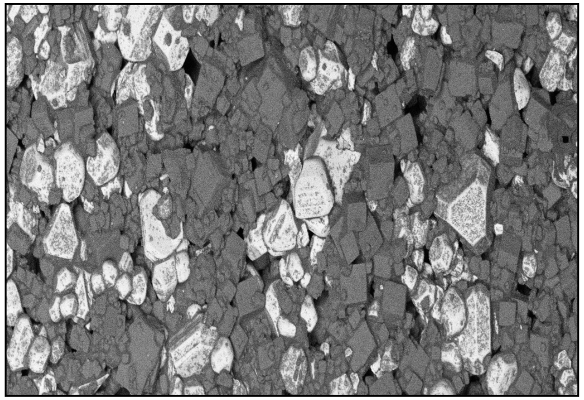
$^{6}LiF/ZnS$:(dopant e.g. Ag, Cu)

- Long term stability - Double exponential decay
  - -Fast: oxidation of highly excited ZnS => passivation layer
  - -Slow: Degradation of ZnS crystal strucutre (sulphur vacancies)

Recovery during beam-down



Walfort, Gruenzweig, Trtik, Hovind, Lehmann, WCNR-10 (2014)



Brightness degradation in electroluminescent ZnS:Cu

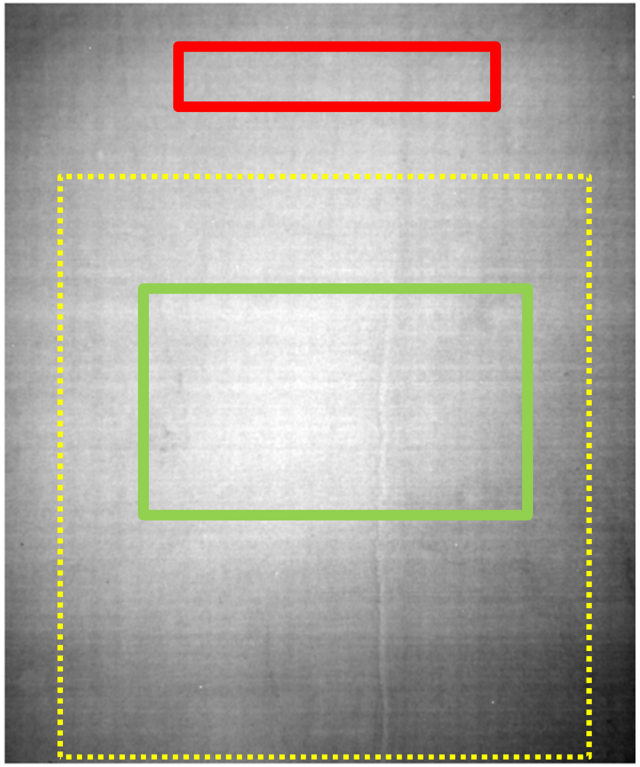
Abstract

Nathaniel E. Brese[a,*], C. Lane Rohrer[b], Gregory S. Rohrer[b]

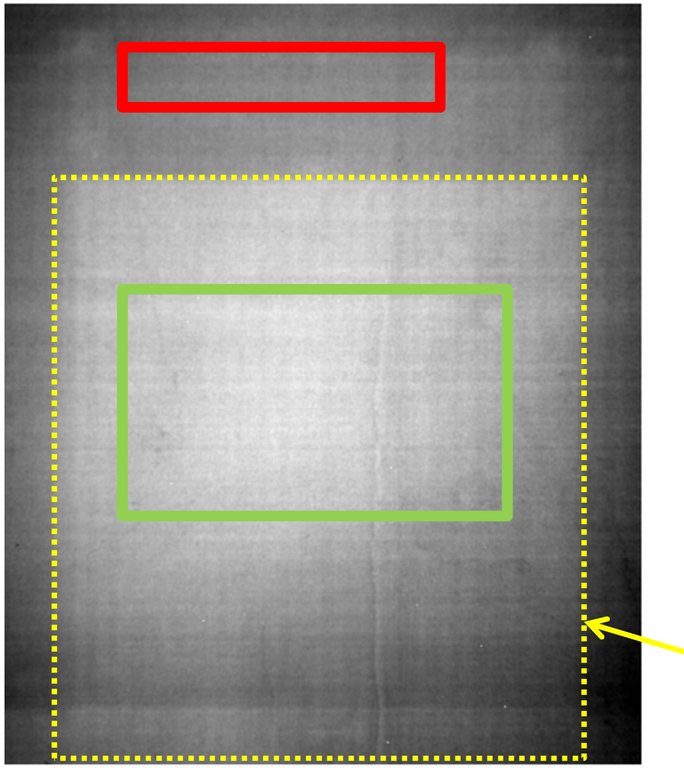
Monte Carlo simulations using crystal chemical constraints have been used to elucidate the copper diffusion mechanisms in copper-doped zinc sulfide. Relaxation around the ZnS|Cu_{2-x}S interface allows facile copper diffusion, particularly in the presence of substitutional oxygen or sulfur vacancies. Copper diffusion is responsible for the brightness degradation in this electroluminescent material. Reducing sulfur vacancies and substitutional oxygen species are outlined as ways to reduce the luminescence decay. © 1999 Elsevier Science B.V. All rights reserved.

Brese et al., Solid State Ionics (1999) 123, 19-24

ZnS light output degradation (neutron images)



1^{st} open beam picture



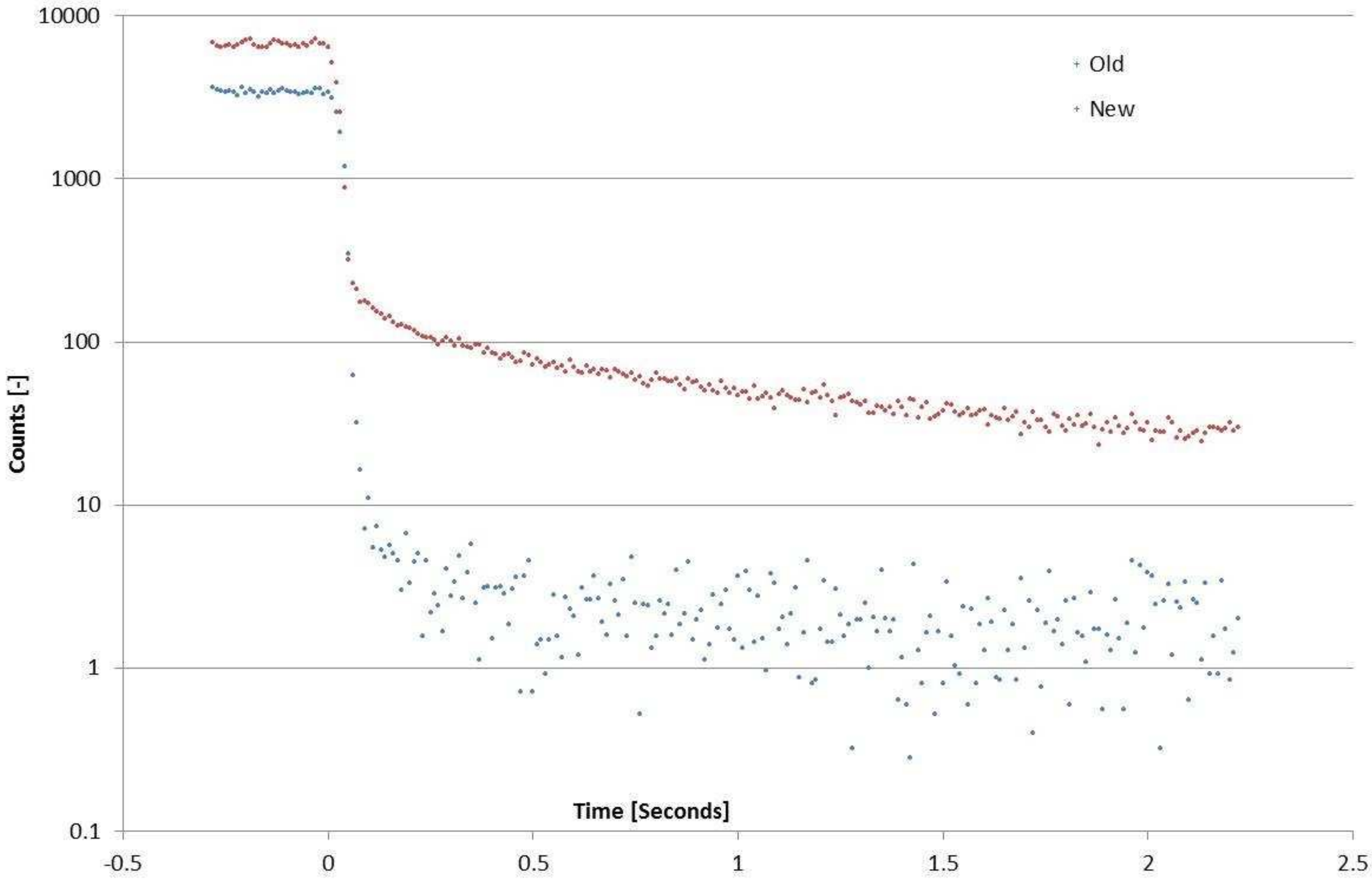
Last open beam picture

Position of the sample

	Initial value	Final value	Degradation
Gray level behind the sample (green)	22681	22011	-3%
Gray level in the open beam (red)	21986	19796	-10%

Courtesy P. Vontobel (2013)

ZnS decay times (afterglow)



Trtik, unpublished data (2014)

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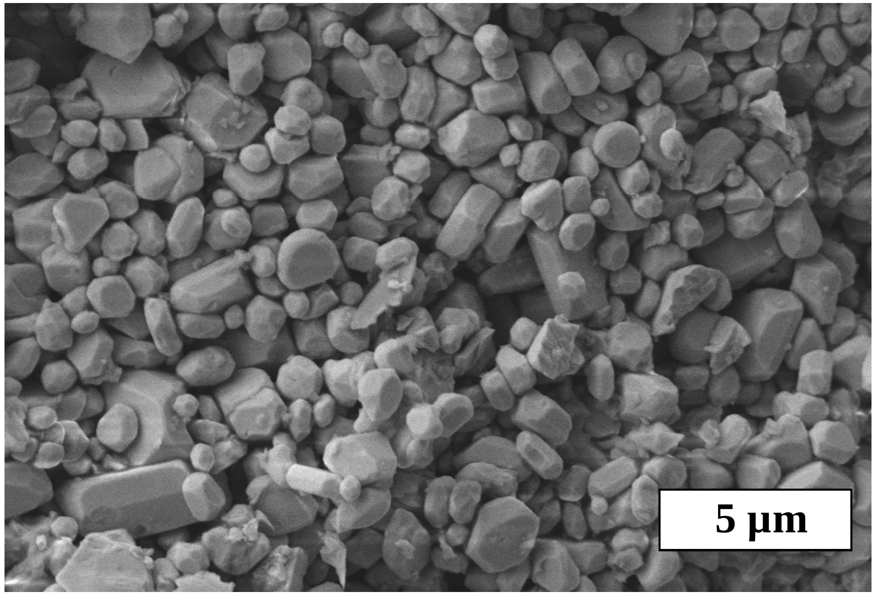
Gadolinium Oxysulfide Gd_2O_2S:(dopant)

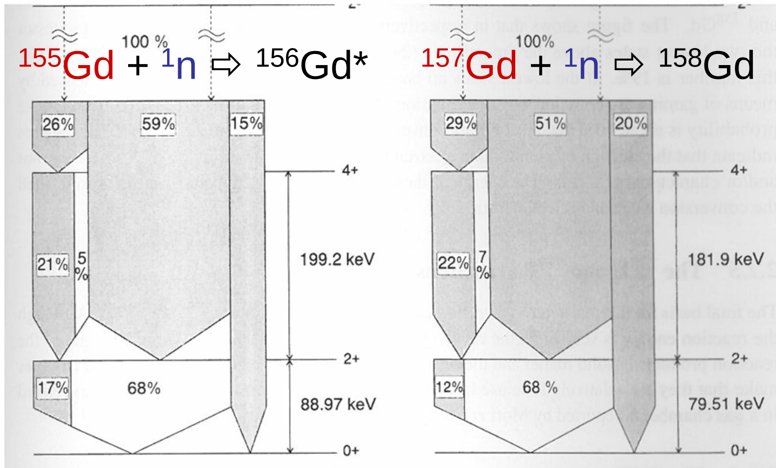
- Gd is the element of the highest cross-section for neutrons (~50'000 barns)
- 99.99% Neutron capture of ^{nat}Gd => 18.43% ^{155}Gd + 81.56% ^{157}Gd
- Gd_2O_2S:Tb is rather stable substance
- Number of ways how to produce Gadox



$^{155}Gd + {}^{1}n \Rightarrow {}^{156}Gd^* \Rightarrow {}^{156}Gd + \gamma$ (7.9 MeV) + conversion electrons

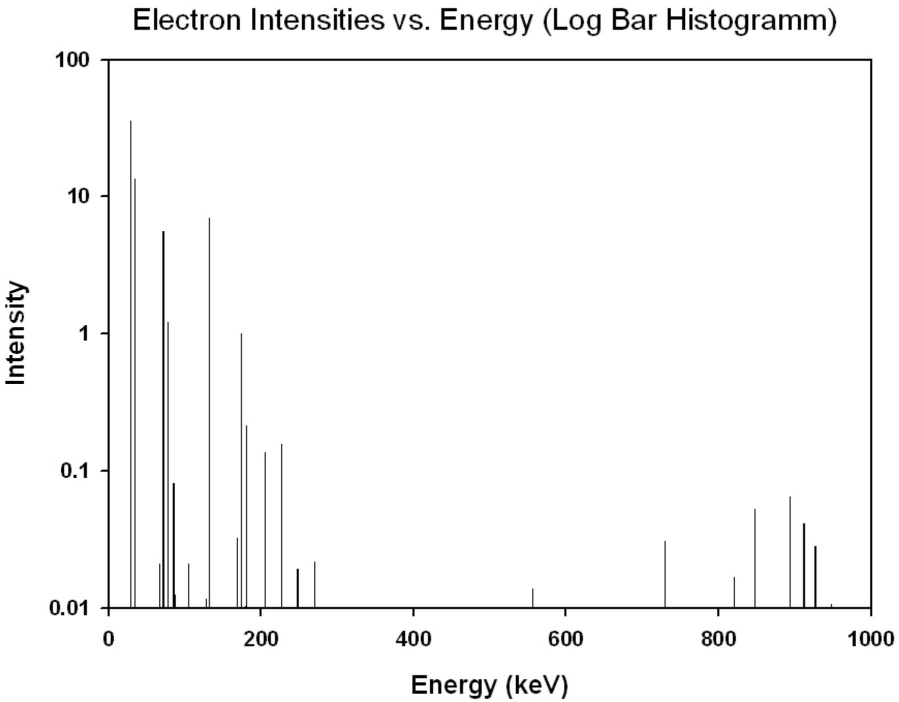
$^{157}Gd + {}^{1}n \Rightarrow {}^{158}Gd^* \Rightarrow {}^{158}Gd + \gamma$ (8.5 MeV) + conversion electrons

- For each captured neutron in Gd, there is at least 1 released gamma-ray
- The conversion electrons are produced only in about 76% of the cases of the neutron capture

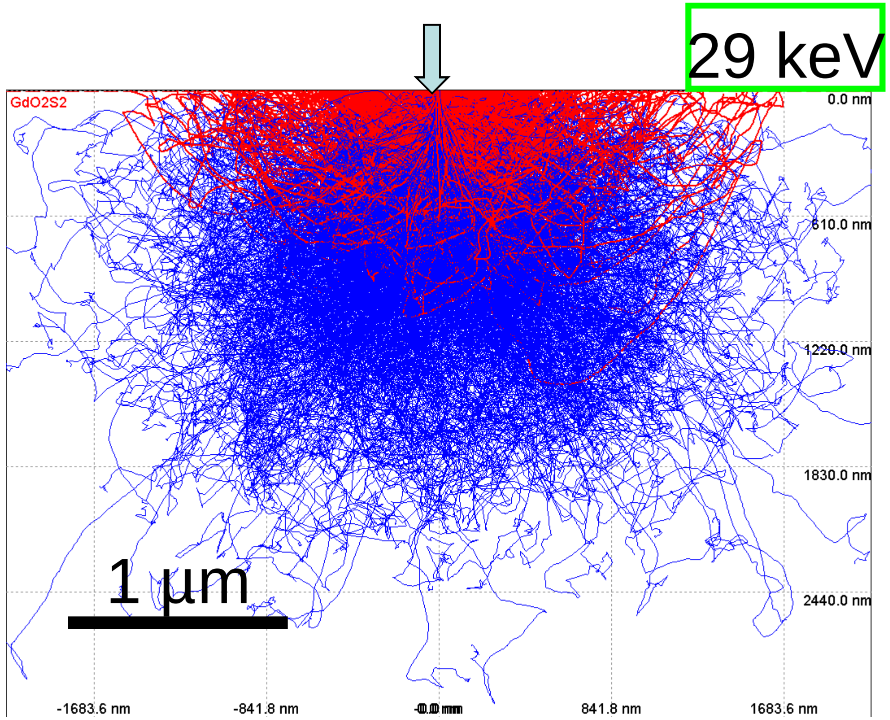


Knittel (1998) PhD. Thesis TU Delft

Gadolinium Oxysulfide Gd_2O_2S:(dopant)



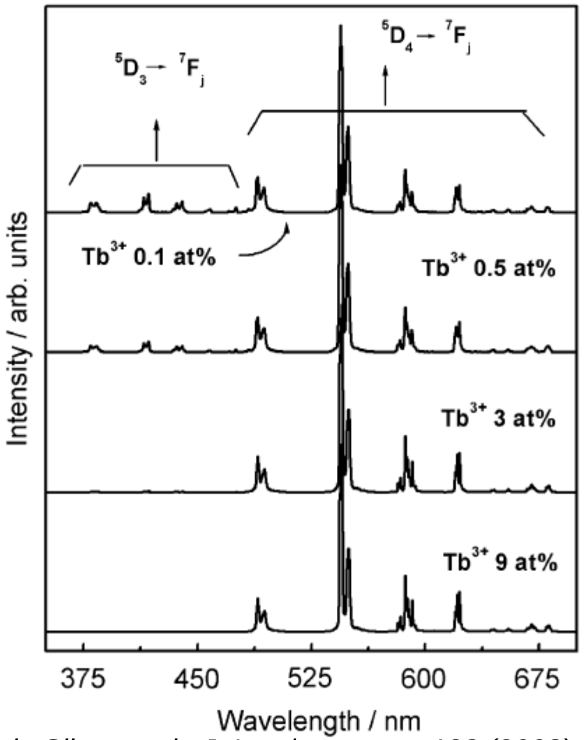
Intensity of internal conversion electrons emitted in the reaction 157Gd (n, γ) 158Gd depending on their energy by 100 neutrons (output data). *Abduschukurov, Appl. Math., 4 (2013) 27-33*



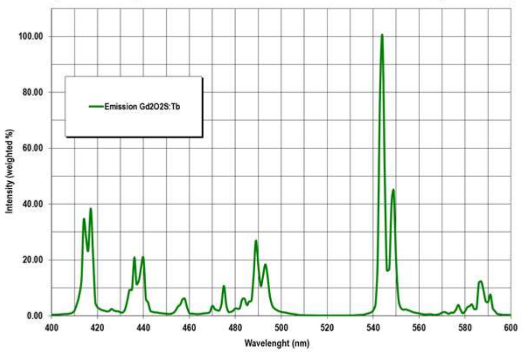
CASINO v2.42 electron microscopy MC softaware

- About 75% of conversion electrons from Gd157 are of sub-35 keV energy
- The travel range in Gadox is in single micrometres domain => OK for very high spatial resolution

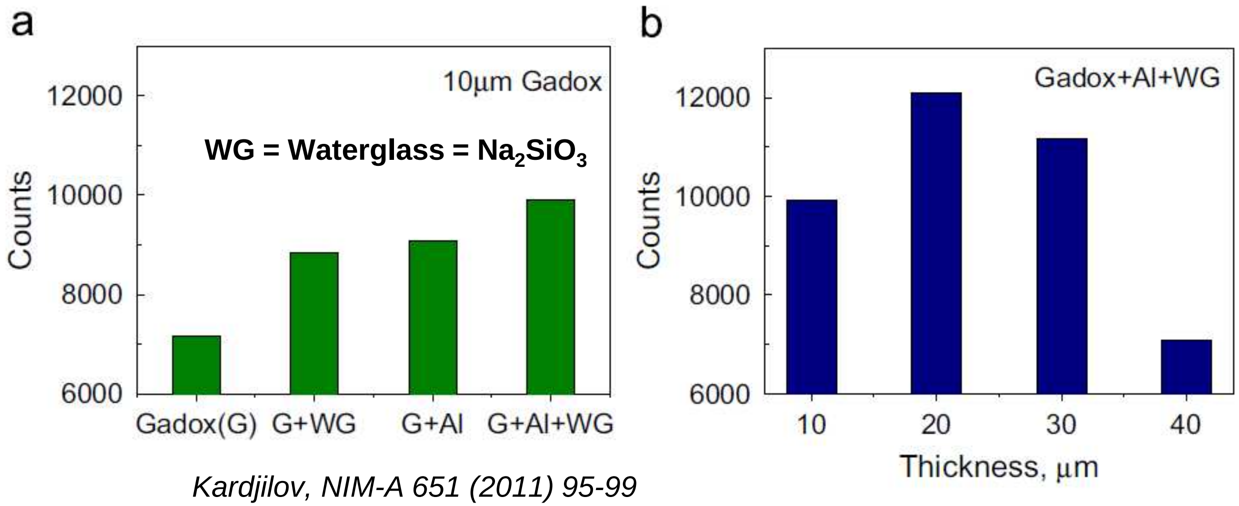
Getting the light out of Gd_2O_2S:Tb



da Silva, et al., J. Luminescence 128 (2008) 1165



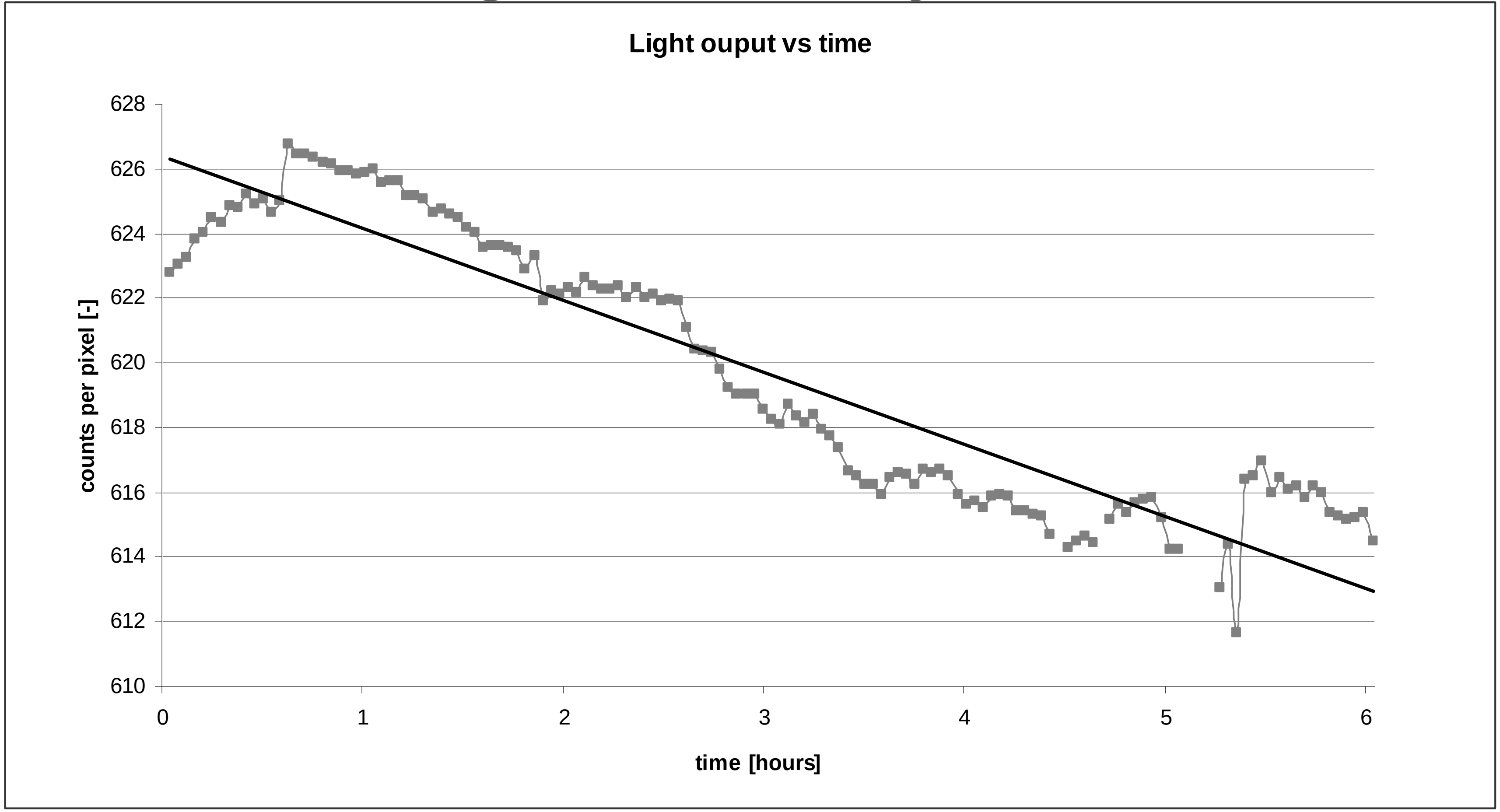
Walfort et al. WCNR-10, 2015



Kardjilov, NIM-A 651 (2011) 95-99

- The emission spectra of Gadox are dependent on the dopant content
- Refractive index of Gadox is about (n=2.3), many internal reflections within particles
- When matched with waterglass (n=1.52), the light is outcoupled more efficiently
- For natural Gadox, the self-shielding starts to be an issue at about 20 µm thickness

„Long-term“ stability of Gadox



- ICON, 80 mm aperture, and a focussing guide, i.e. about 2×10^9 n $cm^{-2}s^{-1}$ (e.g. after 6 hours 4.3×10^{13} n cm^{-2})
- About 2% decrease in the light output over 6 hours of exposure
- Only about 0.02% can be attributed to transformation of $^{157(155)}Gd$ to $^{158(156)}Gd$

Available scintillators supplied by PSI and RC TRITEC

Base material	Emission	Dimension	Thickness	Comment
^{6}LiF / $ZnS:Cu$ (ratio 1 / 2)	530 nm (green)	up to 400 x 400 mm	50 up to 400 μm	High light output and high resolution
^{6}LiF / $ZnS:Ag$ (ratio 1 / 2)	450 nm (blue)	up to 400 x 400 mm	50 up to 400 μm	High light output and high resolution
$Gd_2O_2S:Tb$	447 / 549 nm (blue-green)	up to 100 x 150 mm	10 up to 40 μm	Very high resolution
$Gd_2O_2S:Tb$ / ^{6}LiF	447 / 549 nm (blue-green)	up to 100 x 150 mm	10 up to 50 μm	Very high resolution with enhanced intensity

- Addition of ^{6}LiF gives about 30-50% higher brightness with same spatial resolution☺
- If interested in the purchase, please contact us without hesitation

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Gadolinium isotopes

	Gd-152	Gd-154	**Gd-155**	Gd-156	**Gd-157**	Gd-158	Gd-160	Gd-nat
Content [%]	0.20	2.16	**14.72**	20.41	**15.64**	24.86	22.02	
X-section [b]	735	85	**61’100**	1	**259’000**	2	1	**49’700**

- ^{157}Gd has the highest cross-section for cold and thermal neutrons of all stable isotopes
- The ratio between neutron absorption cross-sections of ^{157}Gd and ^{nat}Gd is approximately 5.

Nuclear Instruments and Methods in Physics Research A 788 (2015) 67–70

Isotopically-enriched gadolinium-157 oxysulfide scintillator screens for the high-resolution neutron imaging

CrossMark

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A R T I C L E I N F O

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Gadolinium oxysulfide
Neutron microscope
Scintillator
Gd-157

A B S T R A C T

We demonstrate the feasibility of the production of isotopically-enriched gadolinium oxysulfide scintillator screens for the high spatial-resolution neutron imaging. Approximately 10 g of $^{157}Gd_2O_2S$:Tb was produced in the form of fine powder (particle size approximately 2 μm). The level of ^{157}Gd enrichment was above 88%. Approximately 2.5 μm thick $^{157}Gd_2O_2S$:Tb scintillator screens were produced and tested for the absorption power and the light output. The results are compared to the reference screens based on $^{nat}Gd_2O_2S$:Tb. The isotopically enriched screens provided increase by a factor of 3.8 and 3.6 for the absorption power and the light output, respectively. The potential of the scintillator screens based on $^{157}Gd_2O_2S$ phosphor for the purpose of the (high-resolution) neutron imaging is discussed.

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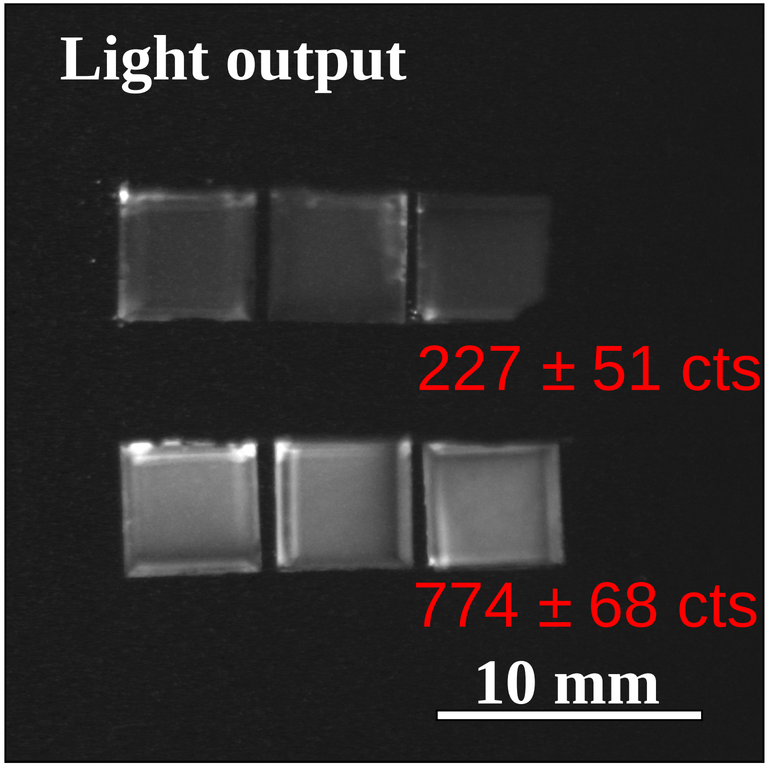
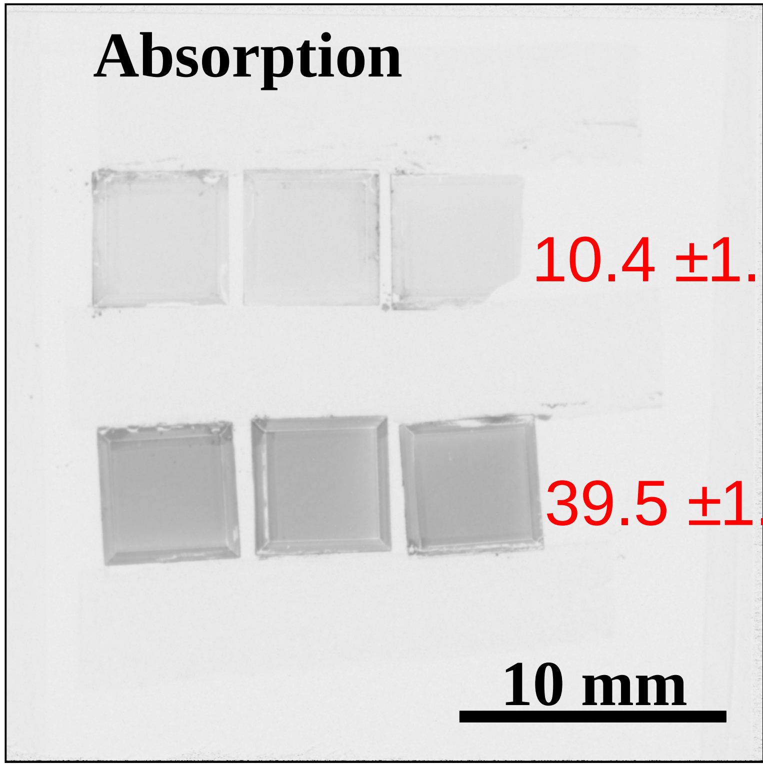
$^{157}Gd_2O_2S:Tb$ vs $^{nat}Gd_2O_2S:Tb$

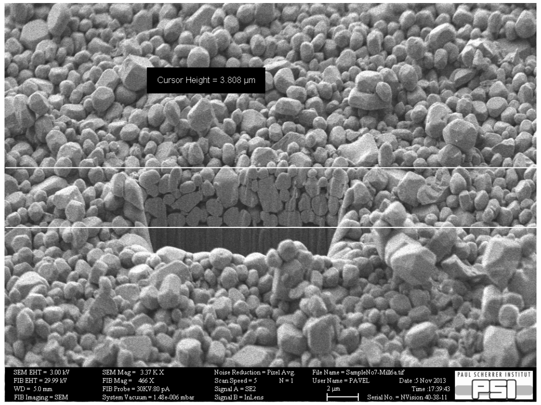
- 6 scintillator plates (2.5 µm thickness) tested in each category using the MICRO-setup





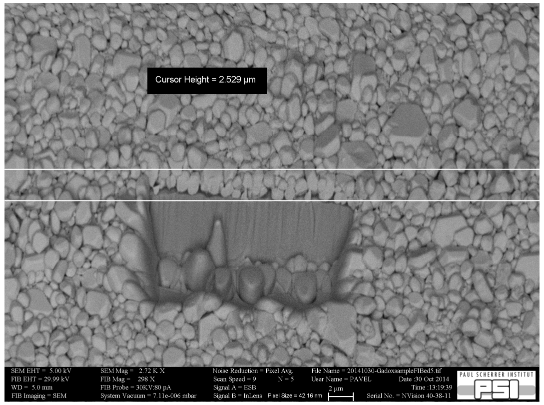
Gain Factors :	Absorption Theoretical	÷ 4.6
	Absorption Measured	÷ 3.8
	Light Output Measured	÷ 3.6

Spatial resolution using very thin Gadox



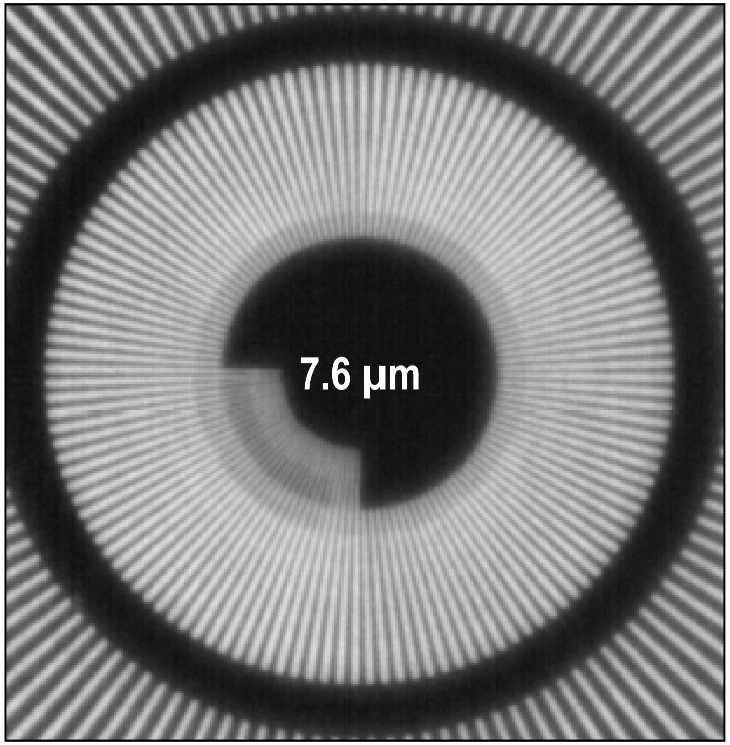
4µm

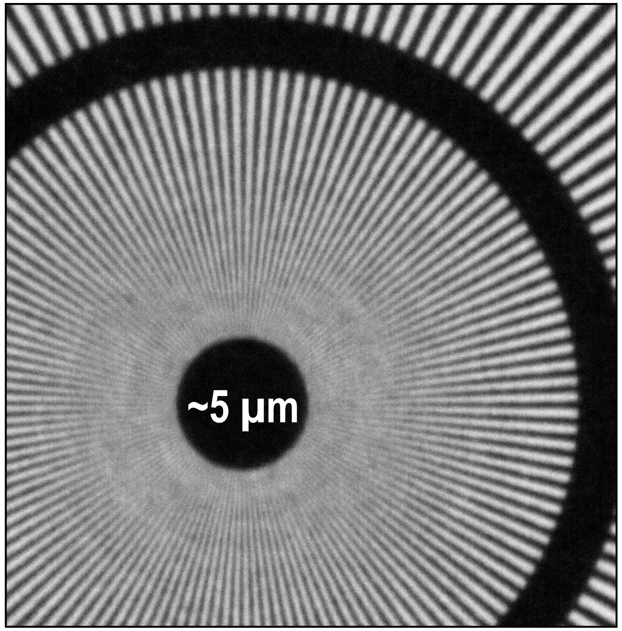
Trtik et al., Physics Proc., (2015)



2.5µm

Trtik & Lehmann, ECNS, 2015

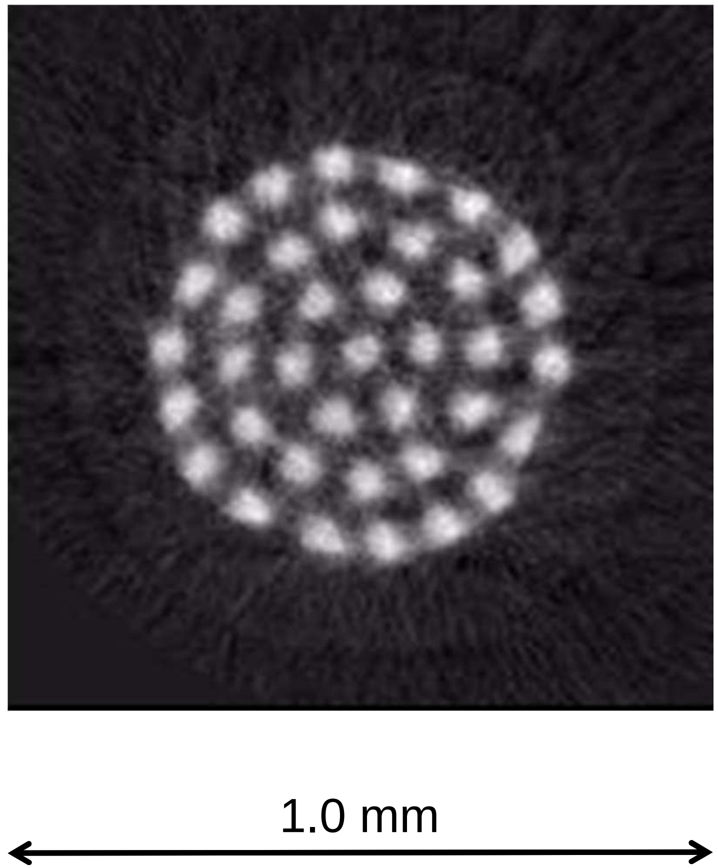




- If interested in the purchase (screen or microscope), please contact me.

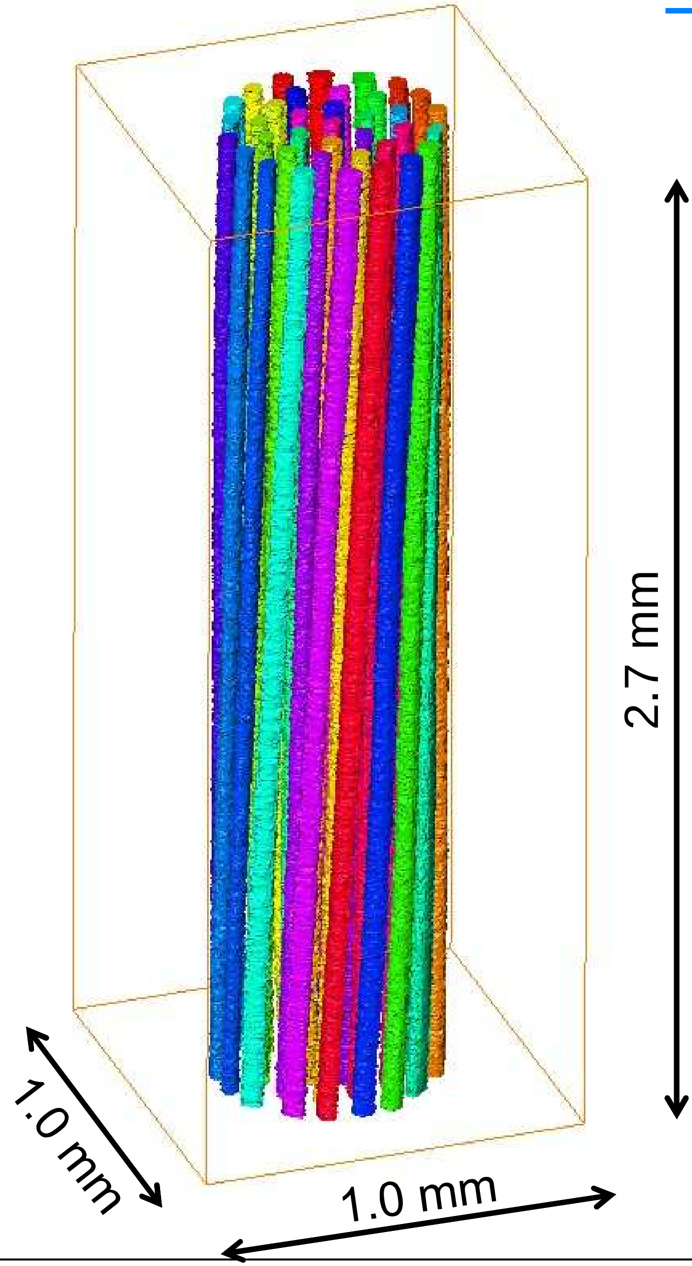
MgB_2 multifilament wire in Ni casing

- Boron 3D distribution



- 4-binned, 5.2 µm pixel size,
- 180 projections
- about 4.5 hours acquisition time

Sample courtesy of Ch. Scheuerlein (CERN)



Alternative scintillators

Alternative scintillators:

Ce-doped Li glass

$Cs_2LiYCl_6(Ce)$ - CLYC

$^6LiGd(BO_3)_3$

GGG:Eu+ (Gadolinium Galium Garnet)

GAGG:Eu+ (Gadolinium Aluminium Galium Garnet)

GdI_3:Ce

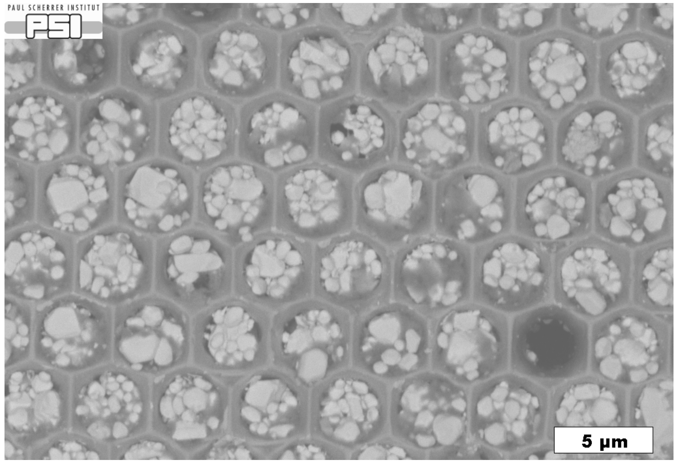
LiI(Eu) – Lithium Iodide

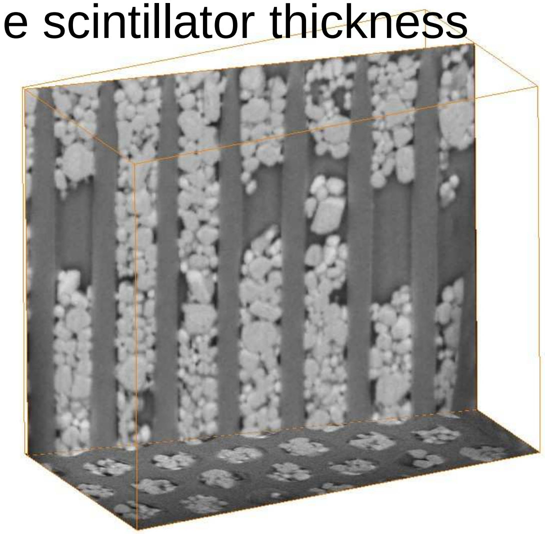
LISe (Lithium Indium Diselenide)

LNI (Lithium Sodium Iodide), LCI (Lithium Calcium Iodide)

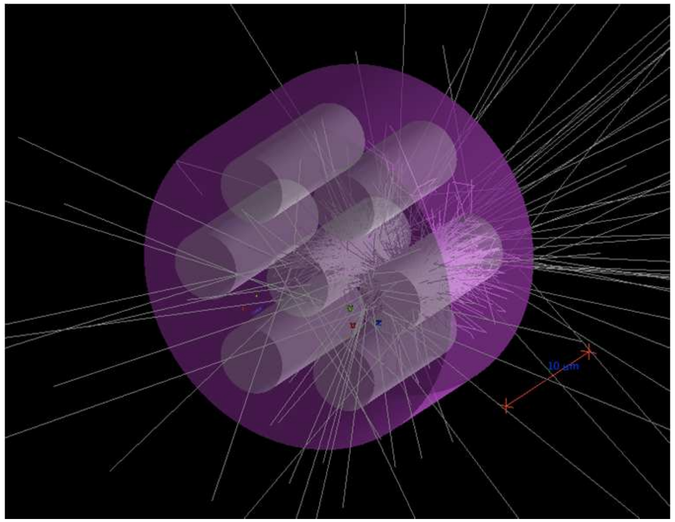
Outlook – microstructured scintillators

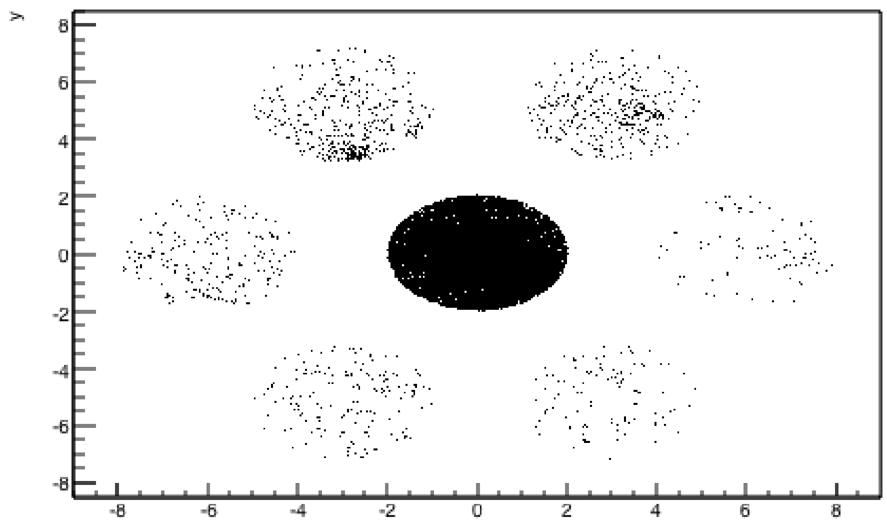
- Well-known concept from X-ray imaging (e.g. Rutishauser, APL, 2011)
- Decoupling of the detector resolution from the scintillator thickness





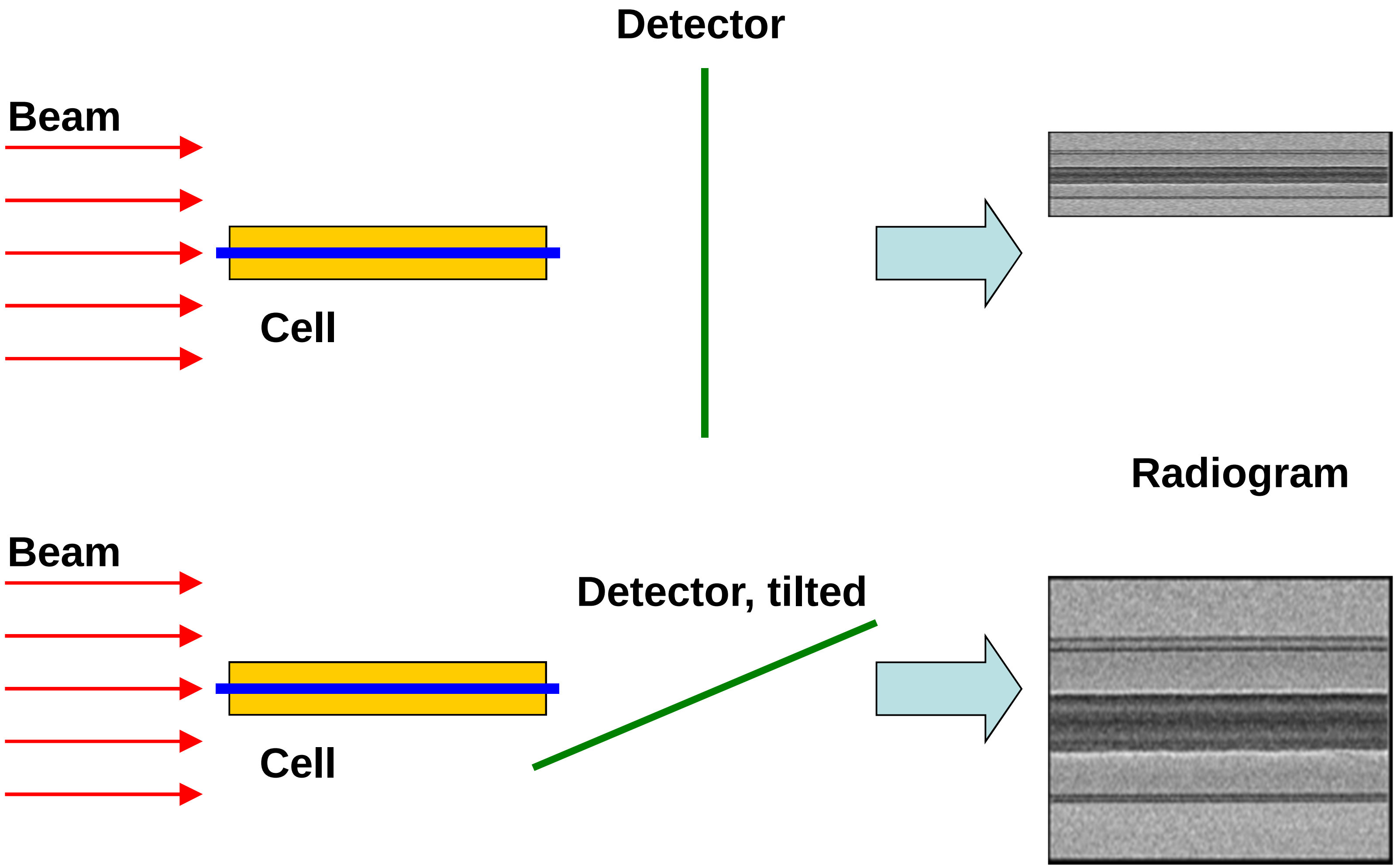
- MC simulations of light output from microstructured neutron-sensitive scintillators





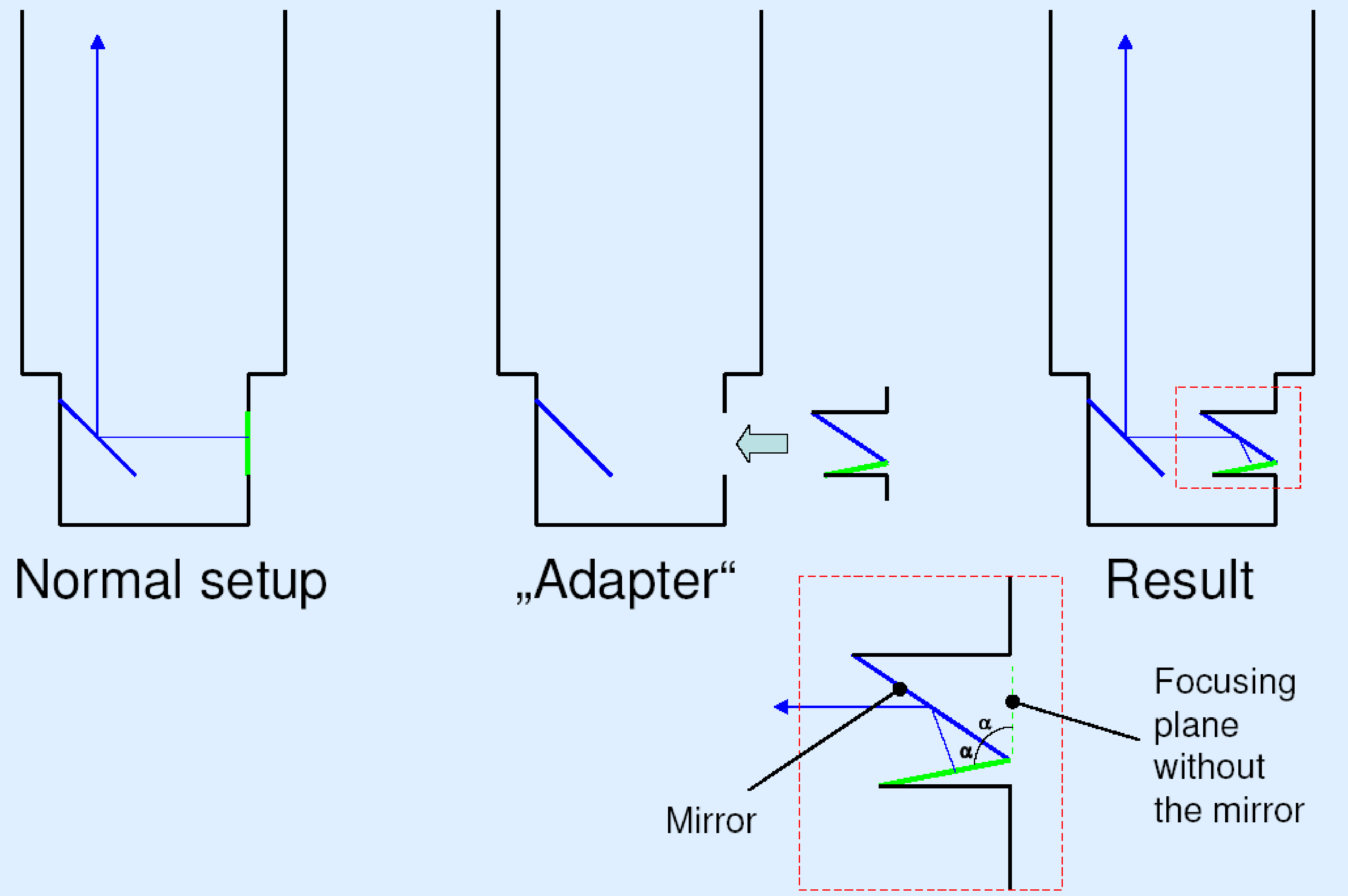
E. Cazalas, M. Morgano, C. David, E. Lehmann, P. Trtik, in preparation (2015)

Resolution improvement – method of tilted screens



Source: P. Boillat, Electrochemistry, PSI

„Tilted Scintillator adapter“



Tilted detector

ANISOTROPIC PIXEL SIZE AND SPATIAL RESOLUTION OF IMAGES!!

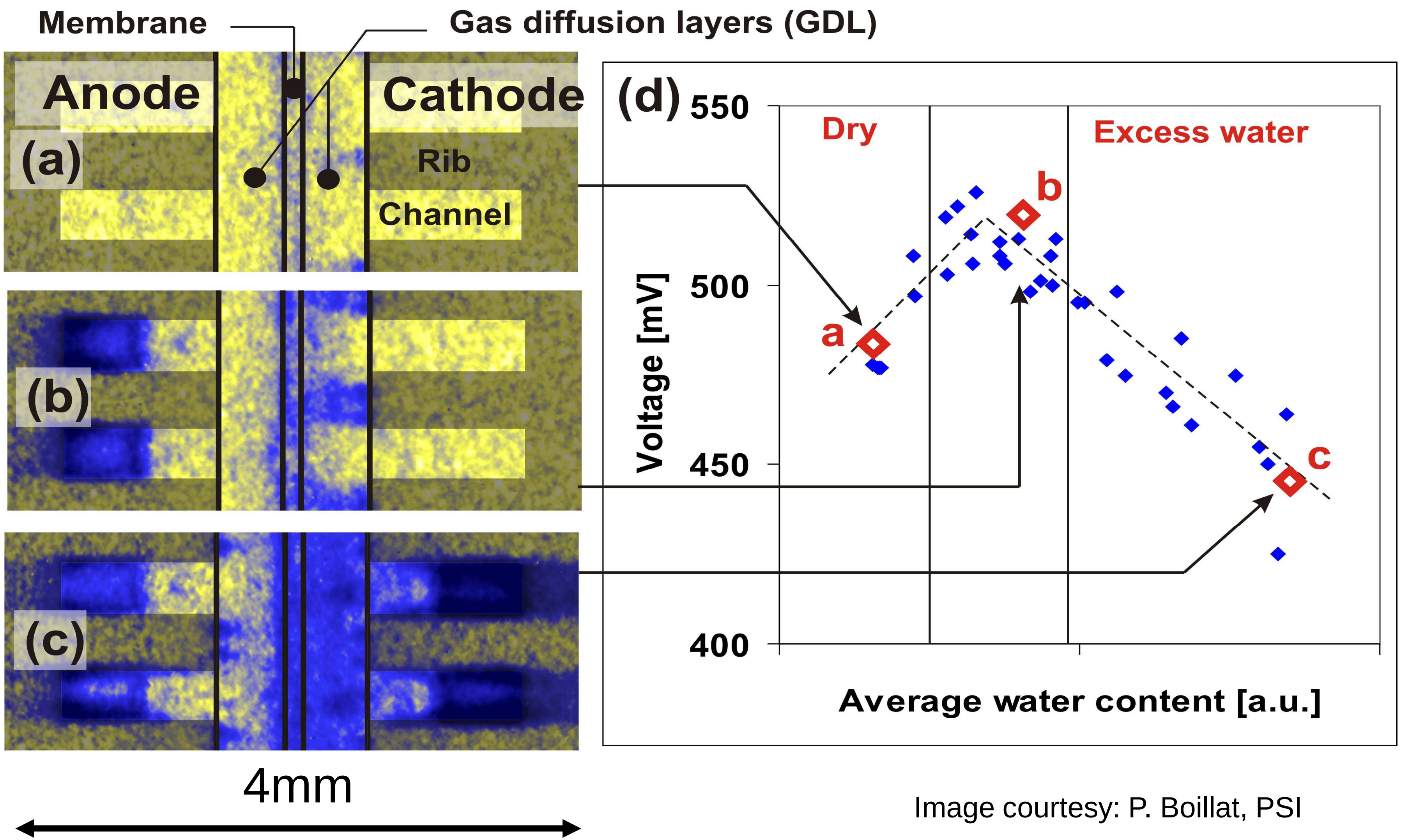


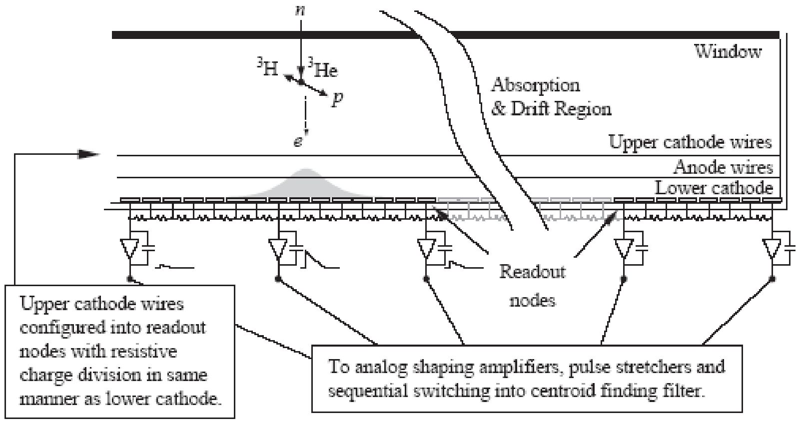
Image courtesy: P. Boillat, PSI

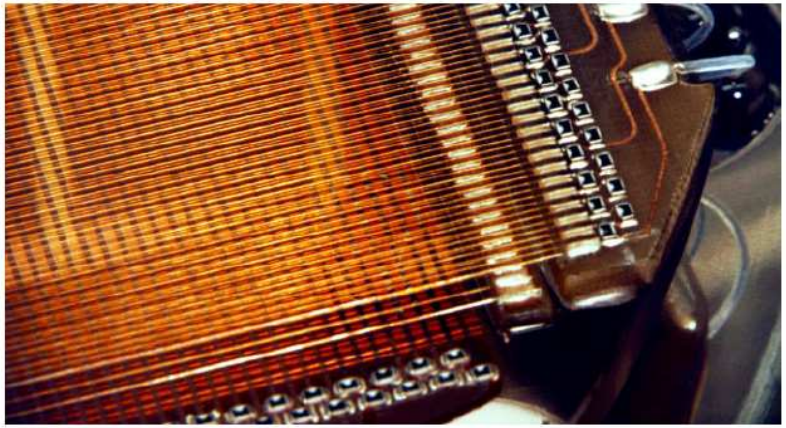
Outline

- A bit of history
- Present state-of-the-art detectors based on neutron sensitive scintillators and light-collection
- Scitnillators – a bit detailed look into them
- Alternative detector options
- Conclusions/Outlook

Gaseous detectors

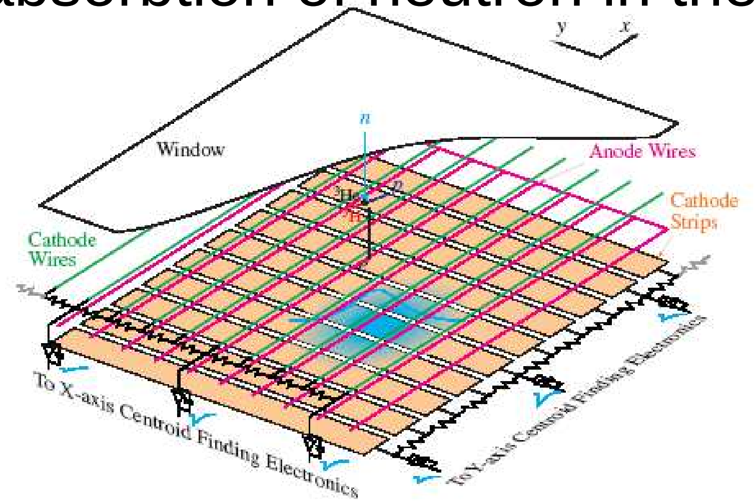
$^{3}\mathrm{He} + {}^{1}\mathrm{n} \Rightarrow {}^{3}\mathrm{H} + {}^{1}\mathrm{p} + 0.77\ \mathrm{MeV}$

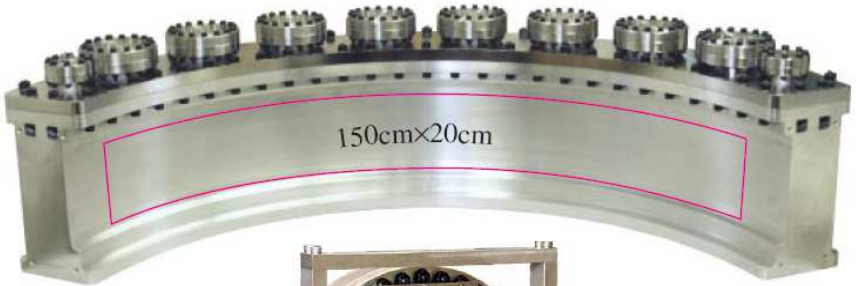


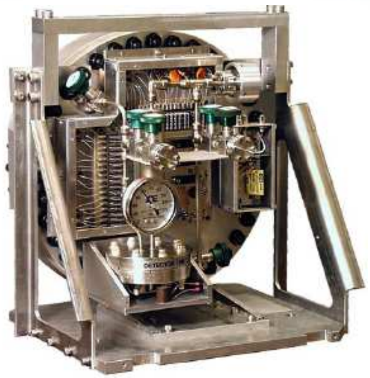


Corner of electrode structure inside a 20cm×20cm detector, showing upper cathode wires, anode wires,

About 20’000 e-h pairs produced by absorbtion of neutron in the gas







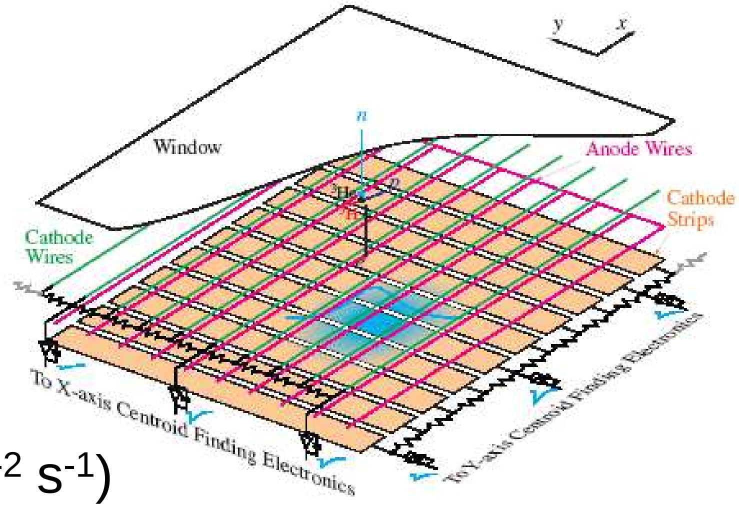
Rear view of a detector showing signal feedthroughs and preamplifiers, as well as the gas purification system.

B. Yu et al. / Nuclear Instruments and Methods in Physics Research A 513 (2003) 362–366

Gaseous detectors

Inert gases (^{3}He, $^{10}BF_3$)

Wire chambers



Large area available (~50x50 cm^2)

High counting rate capability (up to 10^8 n cm^{-2} s^{-1})

Very good temporal resolution

Moderate spatial resolution (0.5-1 mm FWHM)

Need to replace gas every 3-5 years (becomes very expensive)

(^{3}He is becoming limited in availability, therefore change to $^{10}B_4C$)

High pressure (20 bar)– mechanical construction

Imaging plates

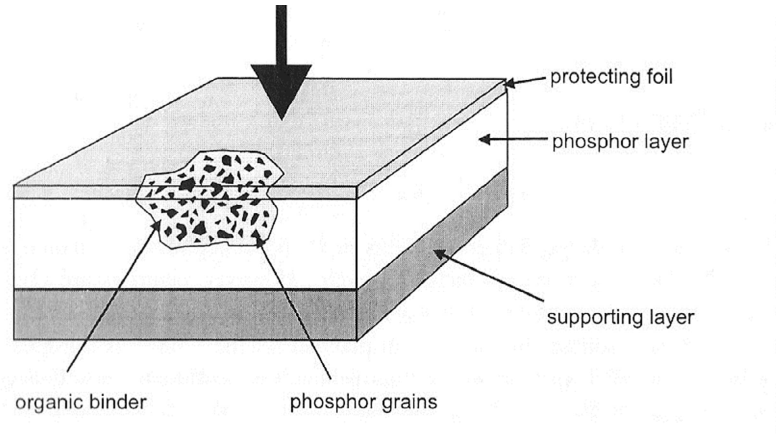
• Photostimulated luminescence by a phosphor excited by neutrons

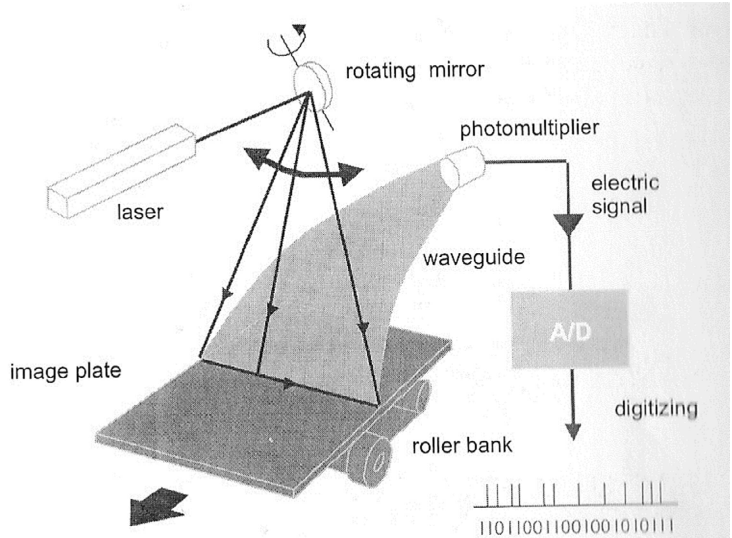
• Imaging plates read by scanner

• Spatial resolution below 100 μm

• Thickness in single-cm regime

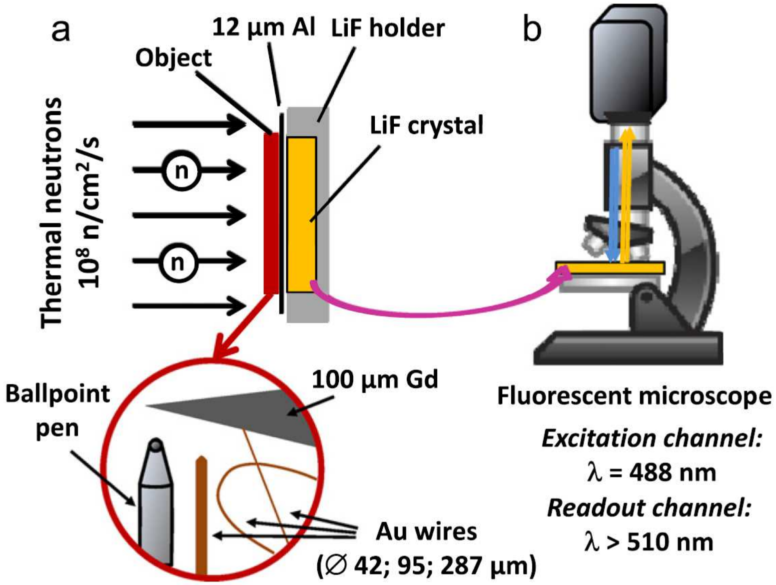
• Useful for only for “single-shot” images in constrained conditions

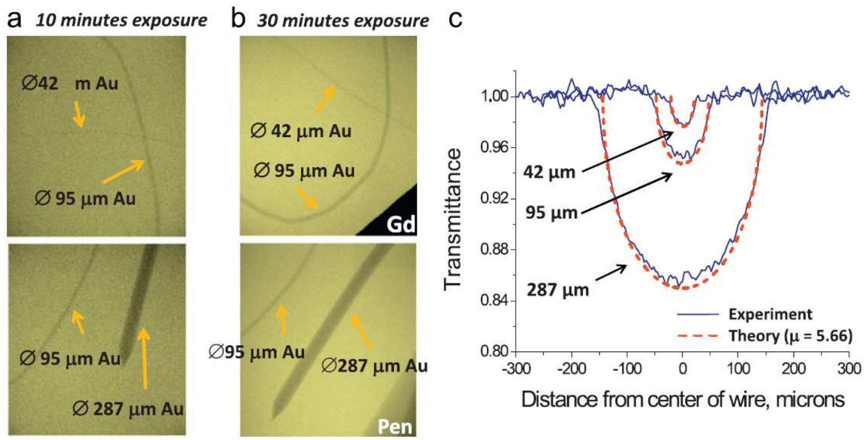




Images courtesy of Knittel (1998)

Neutron detection by color centre formation in LiF



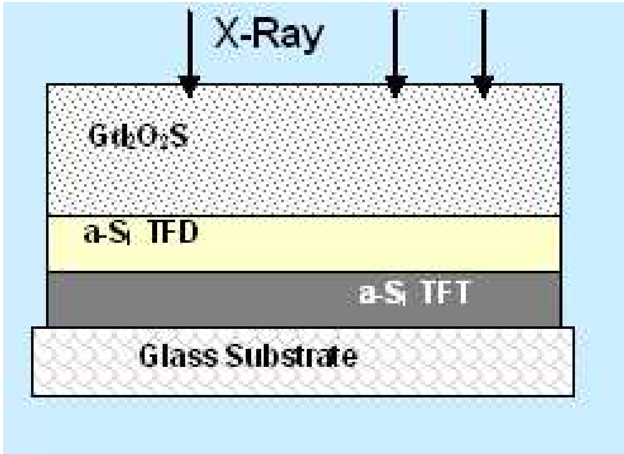


Matsubayashi, Faenov, et al., NIM-A (2010) 622, 637-641

- $^{(6)}$LiF crystals behind samples exposed
- ^{6}Li + n ⇨ ^{3}H (2.73 MeV) + ^{4}He (2.05 MeV)
- The range of ^{3}H (2.73 MeV) ~33 µm
- The range of ^{4}He (2.05 MeV) ~ 6 µm
- The color centres (F) are created by excitation of valence electron to the conduction band with energy 14 eV
- LiF crystal then transferred to a laser confocal microscope
- Moderate exposure times needed
- Indirect method, spatial res. - 5.4 µm

Flat Panel Detectors

- Amorphous Si-panel
- Layer of X-ray/neutron sensitive scintillator
- Very radiation resistant☺
- FPD with about 50 um pixel size are commercially available
- Temporal resolution up to 10 Hz.
- Thickness in single-cm regime
- See presentation by M. Raventos



Hybrid detector based on PILATUS/EIGER

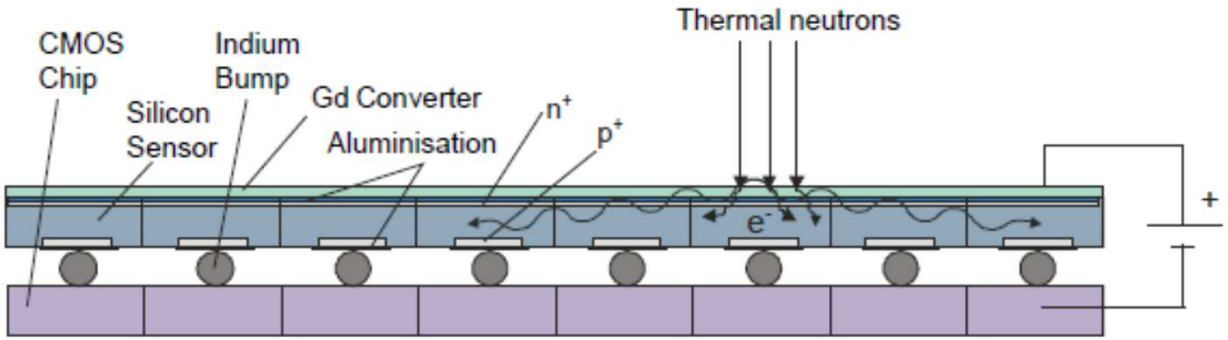


Fig. 5. Layout of the PILATUS pixel detector, which is sensitive for neutrons by a 5 μm thick Gd-157 layer on the top.

- PILATUS /EIGER no dark current, no readout noise CMOS detector
- Single photon counting regime (used for coherent diffraction X-ray imaging)
- Absorber converts neutrons into electrons
- Pixel sizes (120 and 75 um, respectively)
- Limitations on the FOV
- Spatial resolution limited by the charge spread in the absorber/ cross talk between the pixels

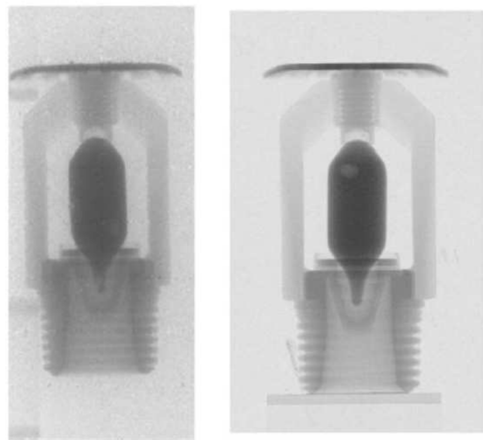
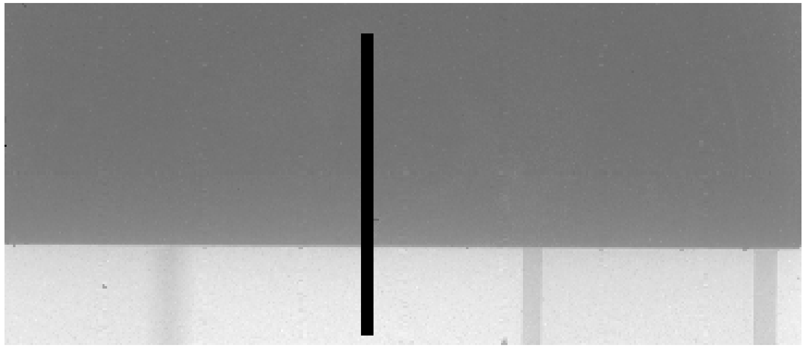
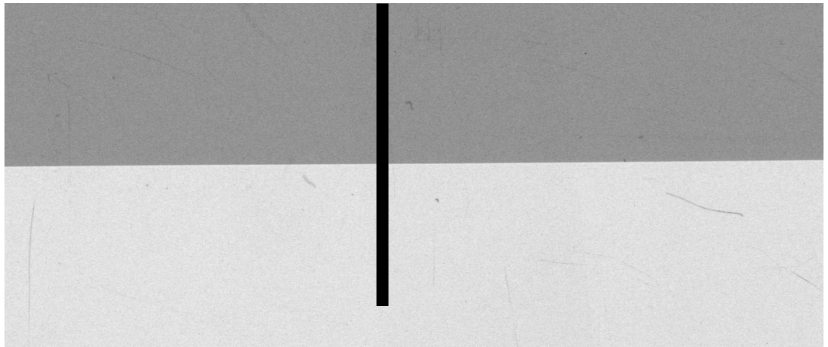


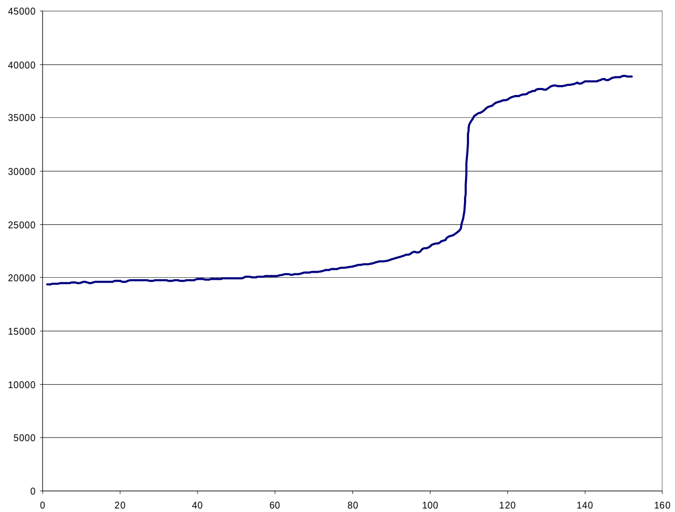
Fig. 7. Radiography image of a sprinkler nozzle made with different imaging systems, PILATUS (left), imaging plate (right).

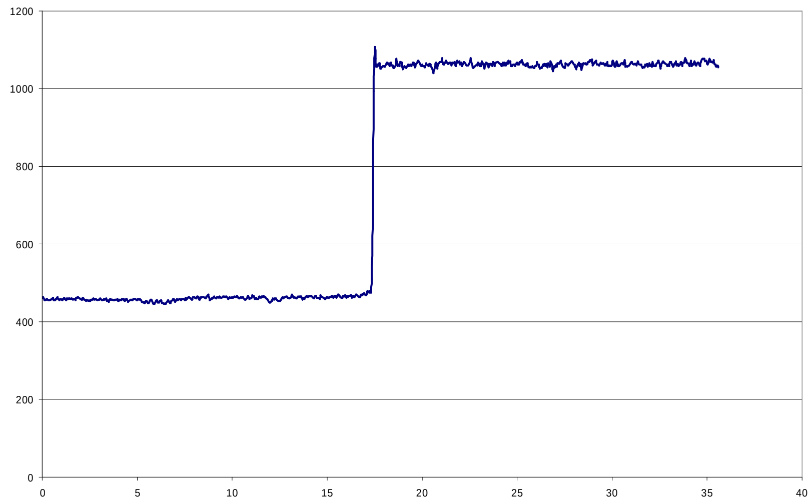
E.H. Lehmann et al. / Nuclear Instruments and Methods in Physics Research A 531 (2004) 228–237

Hybrid based on PILATUS/EIGER detector







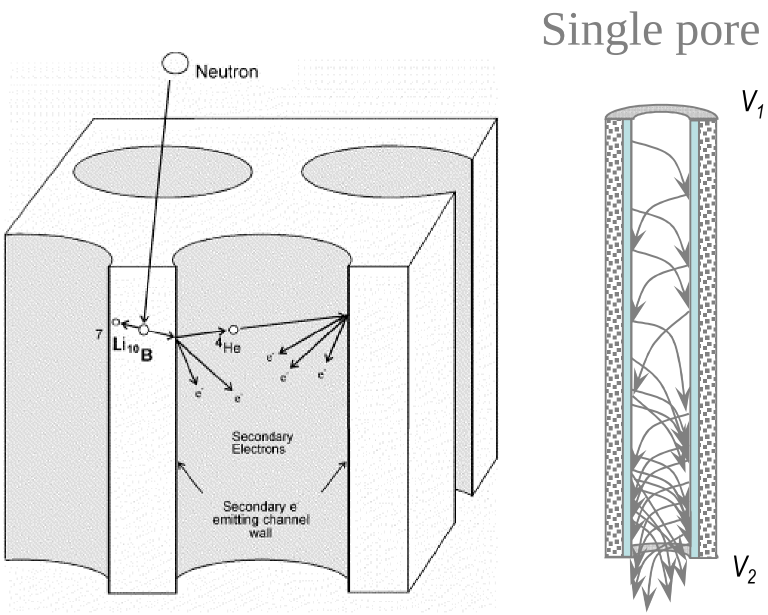


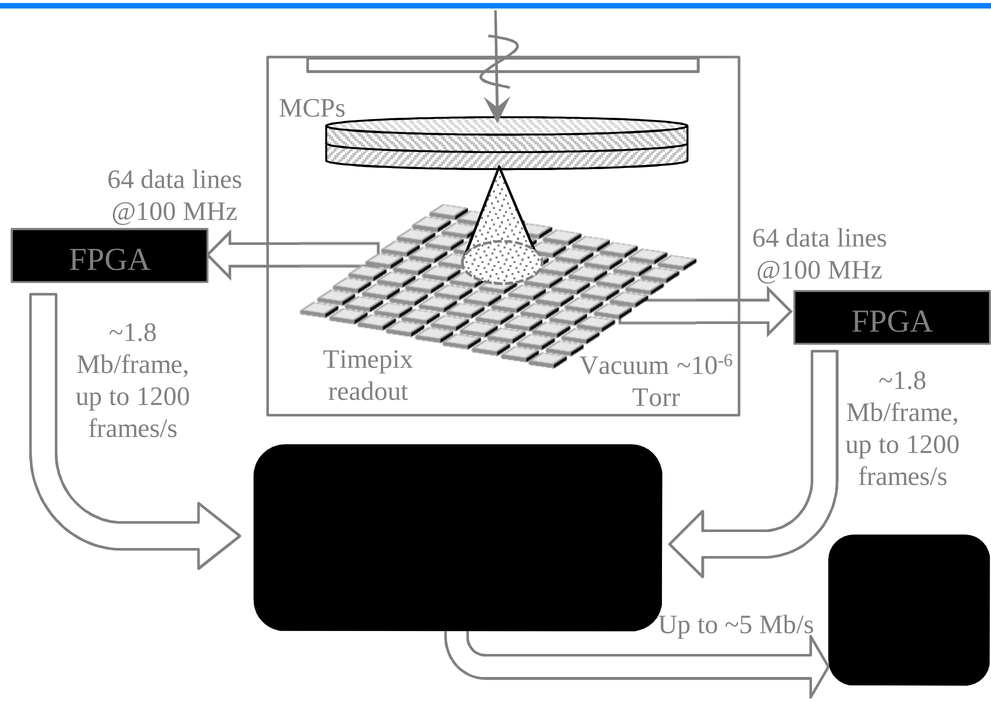
PILATUS-N

NR-Imaging Plate

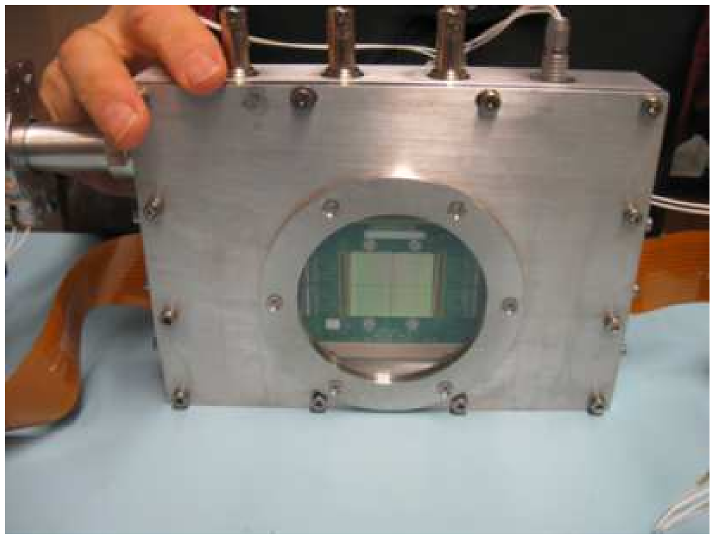
E.H. Lehmann et al. / Nuclear Instruments and Methods in Physics Research A 531 (2004) 228–237

Neutron counting MCP detectors



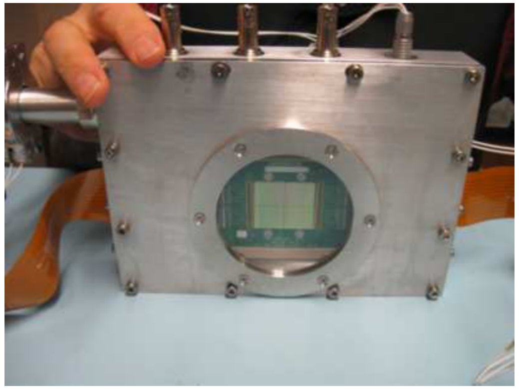


- Based on (MCP) multichannel plate
- Timepix detector (256 x 256 pixels, 55 µm pixel size)
- Each neutron detected: X, Y, Time
- Detection efficiency up to 50%
- Operated in vacuum



A. S. Tremsin, et al., *IEEE Trans. Nucl. Sci.* **52**, 1739 (2005)
O.H.W. Siegmund et al., *Nucl. Instr. Meth. A* **576**, 178 (2007)
A.S. Tremsin, et al., *Nucl. Instr. Meth. A* ***592**, p.374 (2008).*
A.S. Tremsin, et al.,, *Nucl. Instr. Meth. A* (2011)

Neutron counting MCP detectors



28 mm

- Detection of photons, ions, neutrons, alphas, high energy electrons, atoms.
- Detection efficiency for neutrons > 50% for thermal and cold neutrons, <1% for epithermal neutrons.
- Up to ~25000 simultaneous events can be detected.
- Active area 28x28 mm^2 (2x2 Timepix chips).
- Fast parallel readout (x32) allowing ~1200 frames per second with ~320 ms readout time
- Event centroiding (~12 μm resolution, at ~$5x10^6$ events/s) or 55 μm resolution at >$5x10^8$ events/s.
- Time resolution can be ~20 ns at ~$2.5x10^7$ events/s rates with 55 μm resolution.
- Timing within frames – TOF(energy) or dynamic processes can be studied. Wide energy range or most phases measured in one experiment.

TimePix hybrid detector

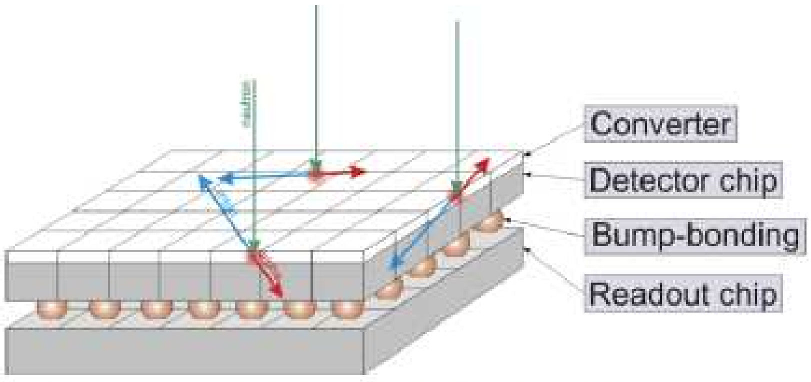


Fig. 2. TimePix device with 300μm thick Silicon sensor chip covered by a ^{6}LiF converter with illustration of a neutron conversion in the converter layer.

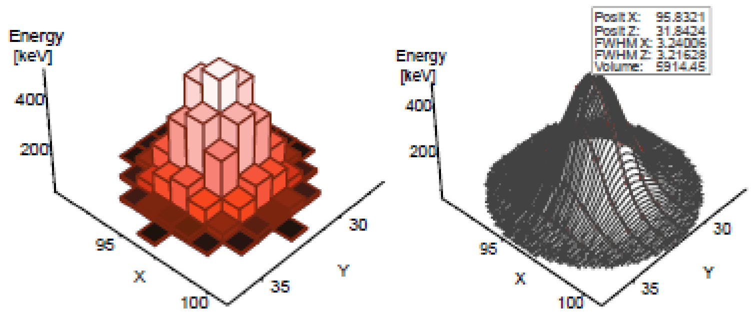


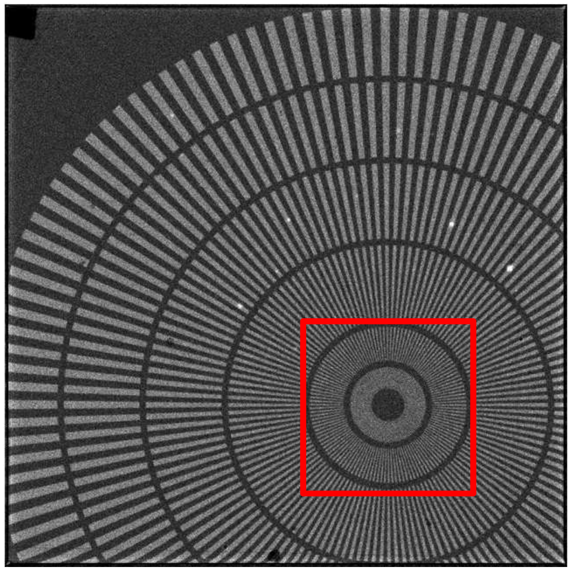
Fig. 4. Cluster of pixels (left) caused by a single 5.5 MeV alpha particle. The detector was operated in TOT mode. The response of each pixel was translated to energy (see Fig. 1). The cluster is perfectly gaussian shaped (right).

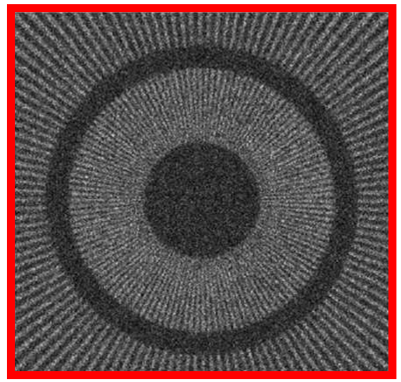
Area: 14x14 mm^2
Limited

High spatial resolution:

3.8 µm (low count rate)

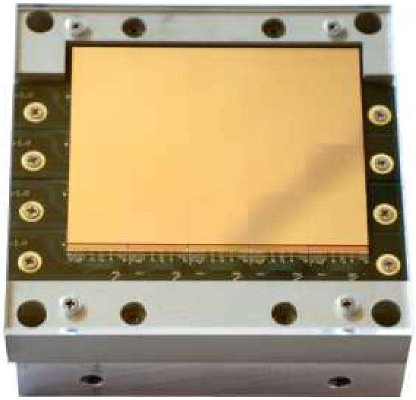
Timing resolution:
10 ns





J. Jakubek, et al., "Energy (TOF) and Position Sensitive Detection of Ultra Cold Neutrons with Micrometric Resolution Using the TimePix Pixel Detector ", 2008 IEEE Nuclear Science Symposium Conference Record N42-1

WidePix hybrid detector



WIDE*PIX*$_{4x5\ \ 10x10}$

- 1280x1024 pixels (6.5 Megapixel)
- 55 um pixel size
- 10 frames per sec

J. Jakubek et al., Czech Technical University

Future outlook

- Present limit of the scinitillator-and-camera neutron imaging is at about 5 μm

- Physical limit by intrinsic properties of the scintillator screen

New approaches:

- ILL beamport with foreseen flux 6 x 10^9 n cm^{-2} s^{-1}

- NIST neutron microscope based on neutron achromatic Wolter optics (*Liu, Hussey et al., APL, 2013*). Current resolution of this microscope 75 μm.

+ one crazy notion on the top:

How precisely are we able to detect inertial mass?

7 Zg (zeptograms) = 3000 Daltons = 7 x 10^{-21} g

Yang et al. 2006 Zeptogram-scale Nanomechanical Mass Sensing

^{135}Xe (2’000’000b)+ ^{1}n ⇨ ^{136}Xe (stable); ^{135}Xe instable $t_{1/2}$=9.2 hours ⇨ ^{135}Cs

Conclusion & Acknowledgements

- Neutron Detectors reviewed

- The scintillators are at the heart of the standard CCD/sCMOS-camera detectors

- There are still number of ways for the future development of higher-performance neutron-sensitive (microstructured) scintillators.

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