PAUL SCHERRER INSTITUT

Development of Cold-/Fast-Neutron THGEM Imaging Detectors for Investigation of Thermal-Hydraulic Phenomena

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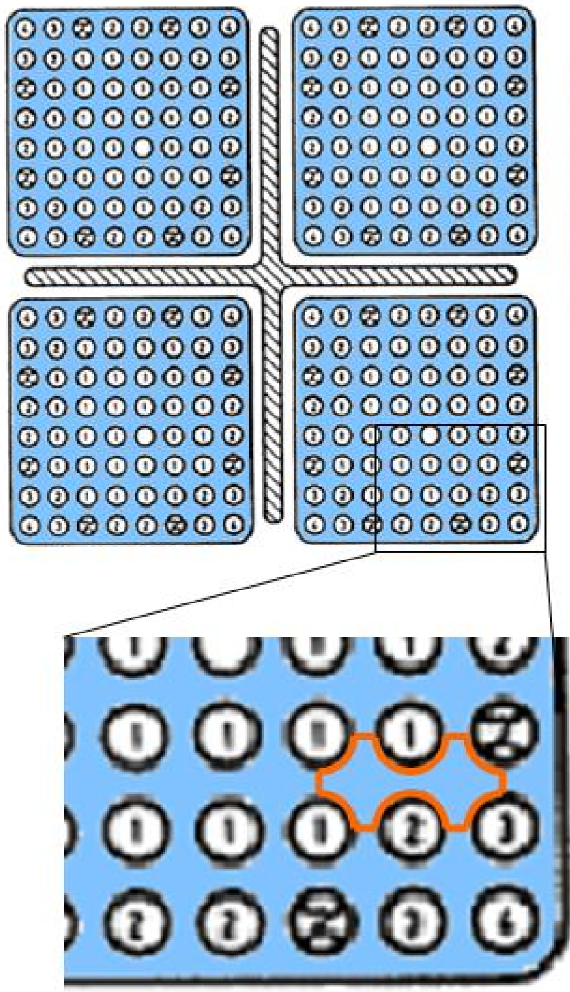
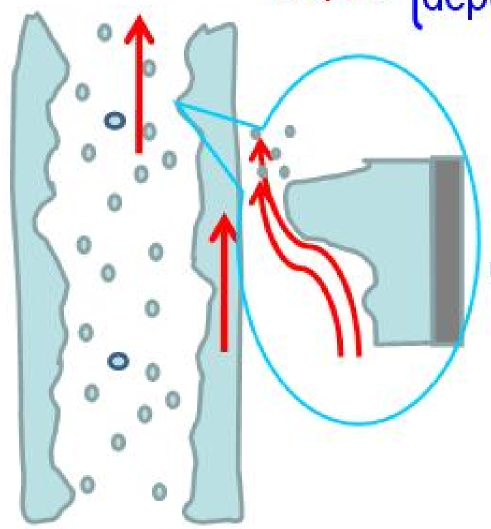
Fluid dynamic studies in BWR Fuel Rod Bundles

Problem: **Boiling crisis** (high quality) -> BWR fuel bundle upper part

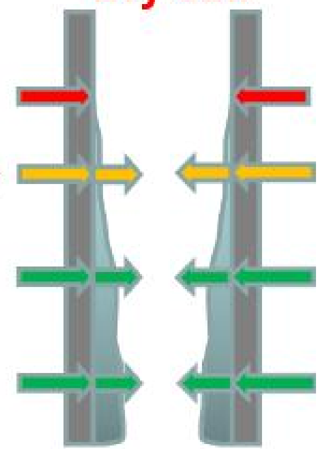


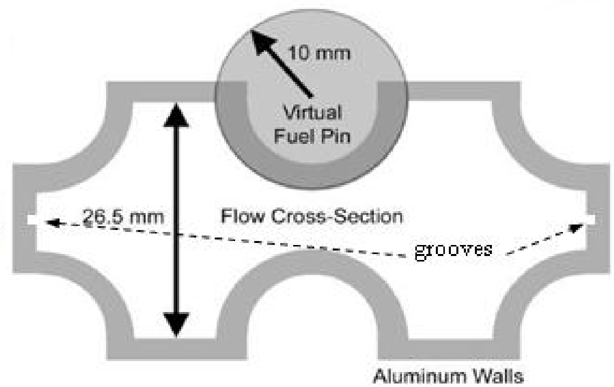
Flow regime: Wavy annular flow:

droplet {entrainment, deposition}



Dry out!

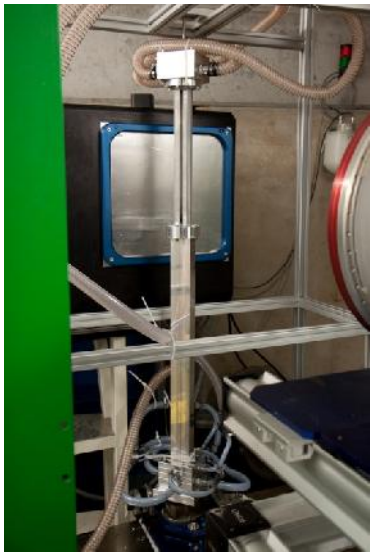




Double subchannel

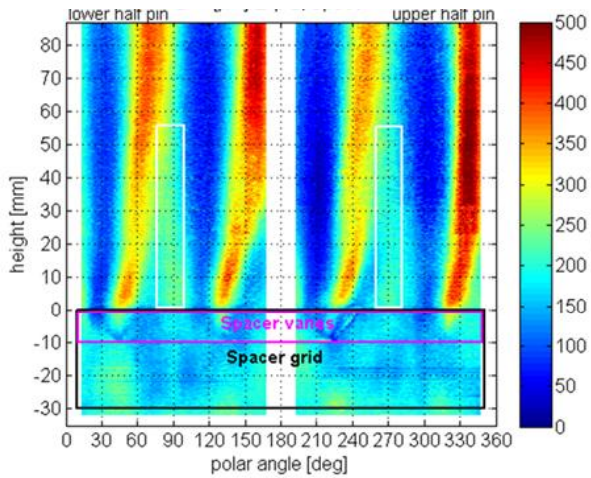
Fluid thickness distribution on fuel pin surfaces

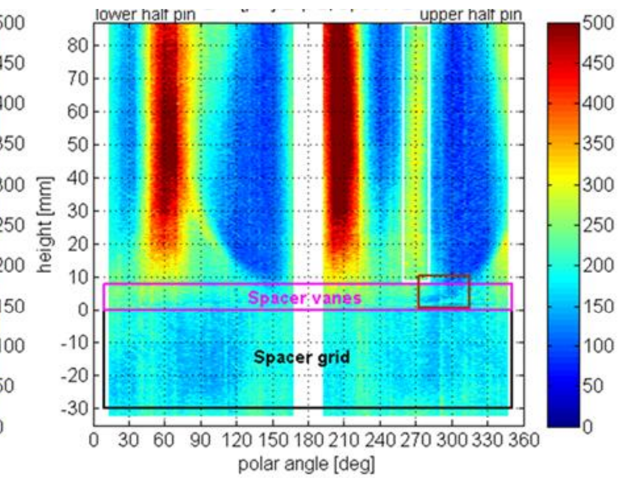
Zboray et al. 2013 Nucl. Eng. & Design 260 188.



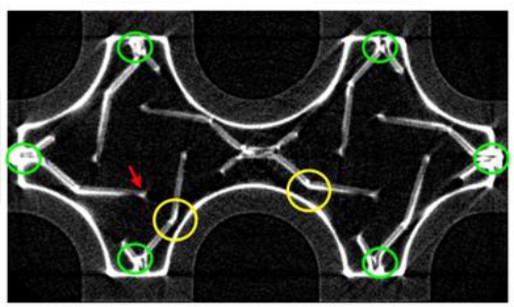
Imaging at the Cold Neutron beam-line (ICON) of SINQ (@ PSI)

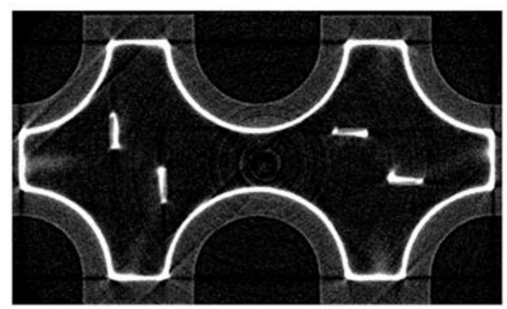
Detector → Scintillator Screen + Intensifier + CCD camera



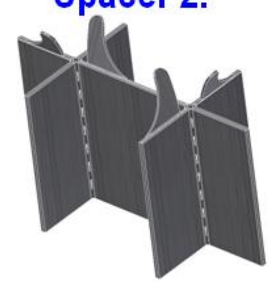


Spacer 1:





Spacer 2:



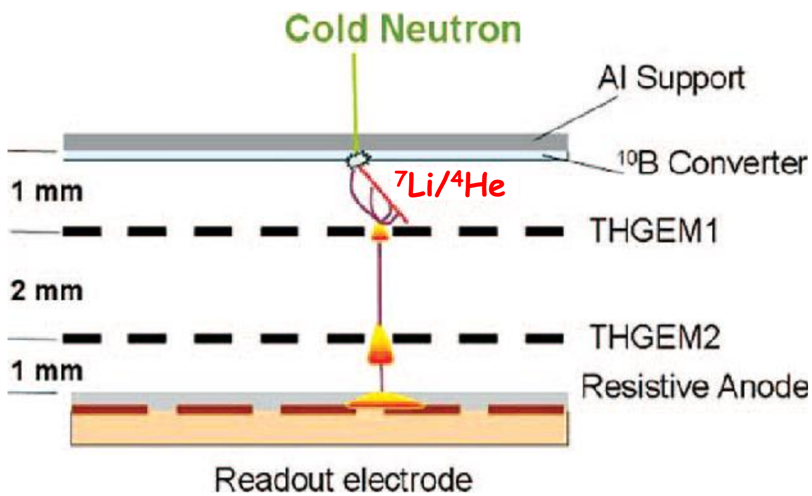
-) Slow and small field of view ➔ MPGD technologies

-) More Contrast and Thicker Fluid Films ➔ Fast neutron

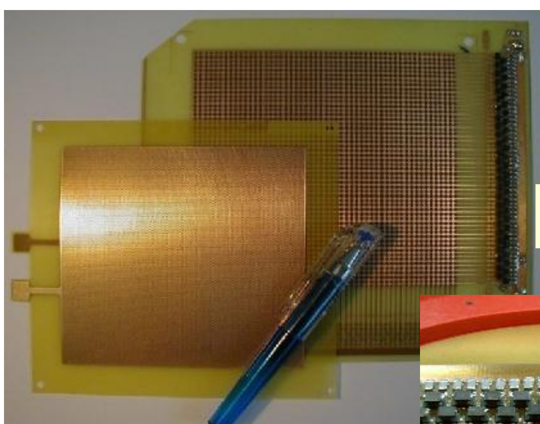
2D Imaging with Cold Neutrons

Cortesi et al. 2013 RIS 84 023305

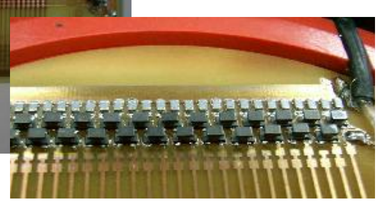
Cold Neutron 10x10cm^2 radiography



THGEM
- 2-sided pad-string anode
- Delay-line readout (SMD)

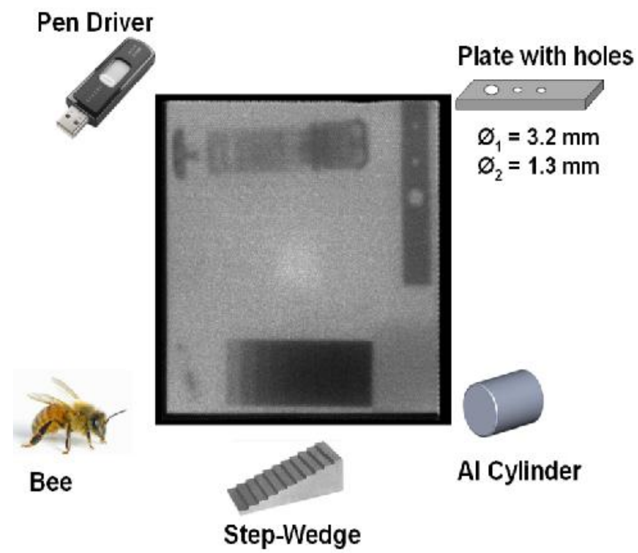


2 mm pitch, 1.35ns/mm



Ionization electrons are multiplied & localized in cascaded-THGEMs imaging detector.

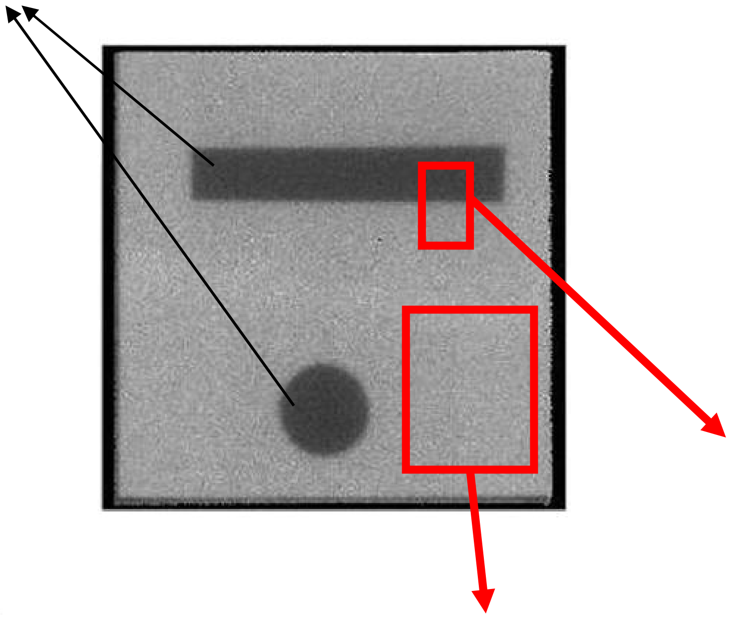
-) Detection efficiency: ~ 5% (cold-n)
-) Counting Rate ~ 3 kcps/cm^2
(Limited by the TDC-based DAQ system)

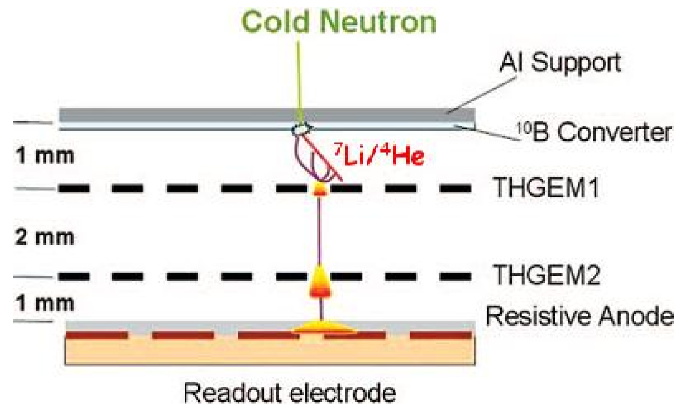


Cold Neutron Imaging (ICON test-beam)

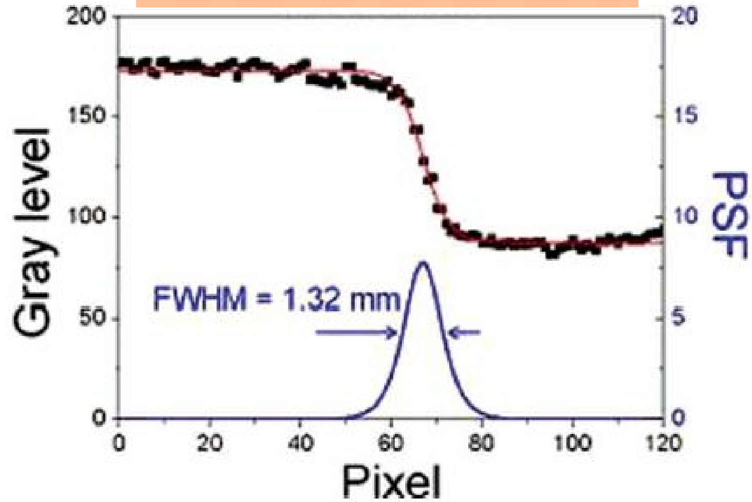
2D Imaging with Cold Neutrons

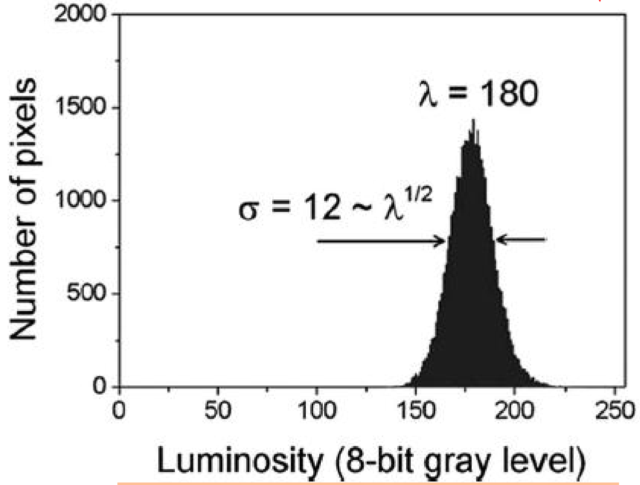
Gd Absorber





Spatial Resolution





Homogeneity

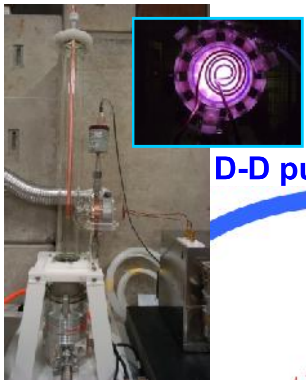
Next
- ➔ Large area detector 30x30 cm^2
- ➔ New charge readout electrode
- ➔ New multi-channel ASIC-based DAQ
- ➔ GEM, higher spatial resolution

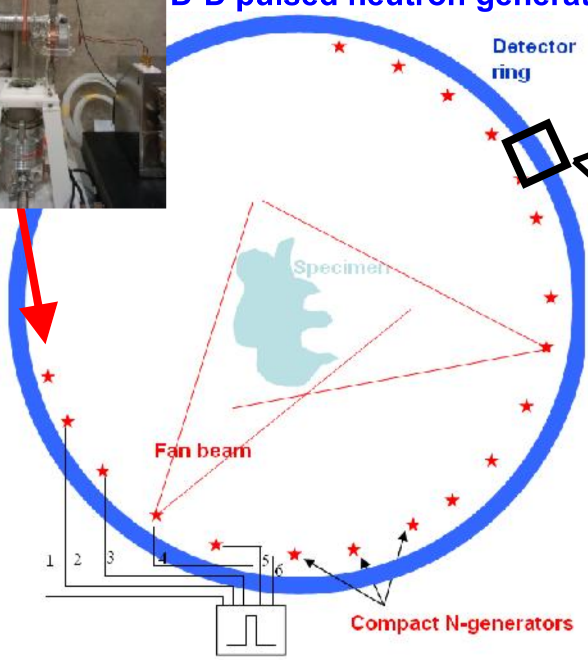
Goal: Fast-Neutron Tomography

TwoFast Project:
- Multiple fast-n point sources (e.g. D-D fusion, 2.5 MeV)
- Ring-shaped Fast-Neutron detector

Detector Requirements:

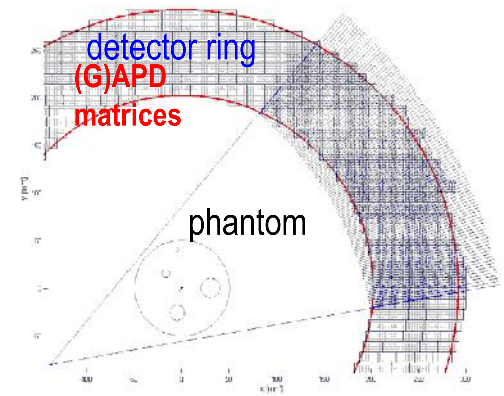
- Good time resolution (ns range)
- High Counting rate (MHz/cm^2 range)
- Good spatial resolution (mm scale)
- High Detection Efficiency (few %)
- Large area (m^2)





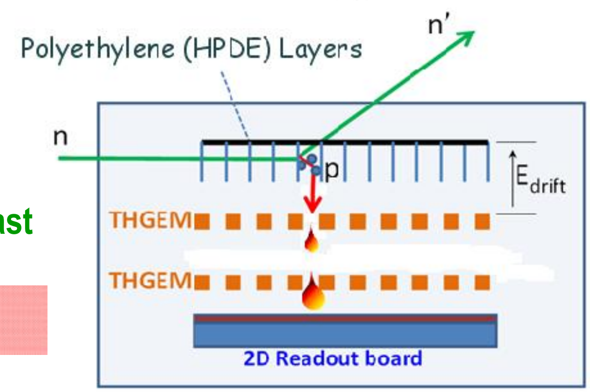
Multiple point source sequentially pulse

Plastic scintillator +(G)APD matrix



Plastic converter +(THGEM) as 2D fast neutron detector

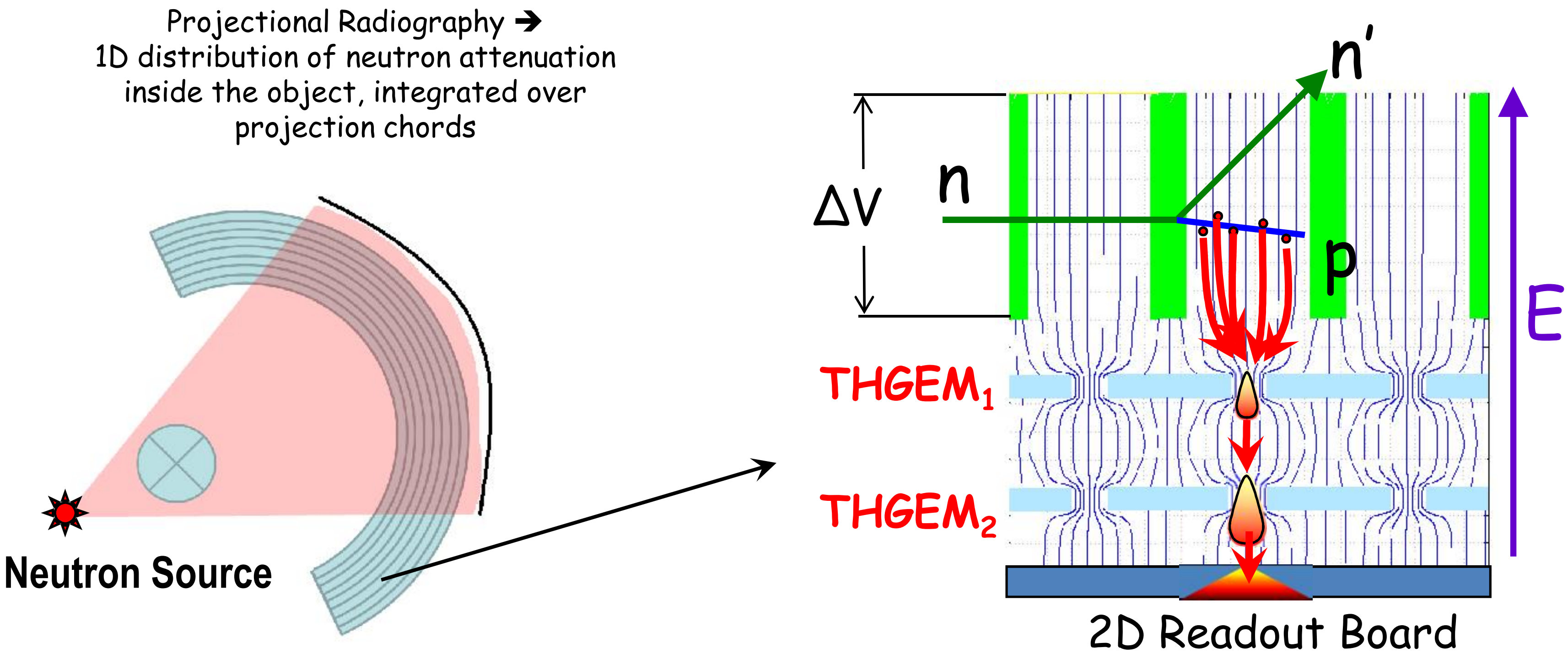
In this presentation



1D High-Efficiency Fast-Neutron Imaging Detector

New THGEM-based Detector Concept

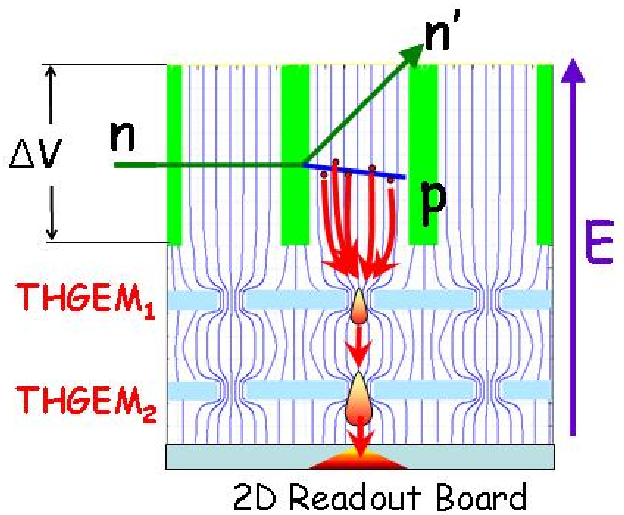
Many Converter n-to-p Layers → high detector efficiency

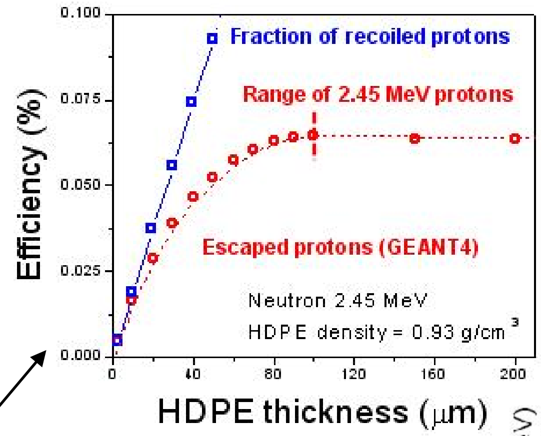


- n scatter on H in HDPE-radiator foils, p escape the foil.
- p induce e^- in gaseous conversion gap.
- e^- are multiplied and localized in THGEM-detector.
- Combine several 1D radiographs → 2D cross sectional tomography.

Cortesi et al. 2012 *JINST 7 C02056*

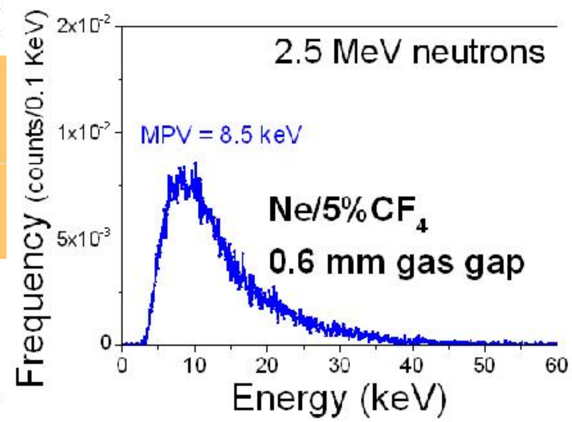
Design of the Converter ➔ Simulation





Min. Thickness ➔ 100 μm

Broad Spectrum of deposited energy ➔ Large dynamic range provided by Ne-mixture

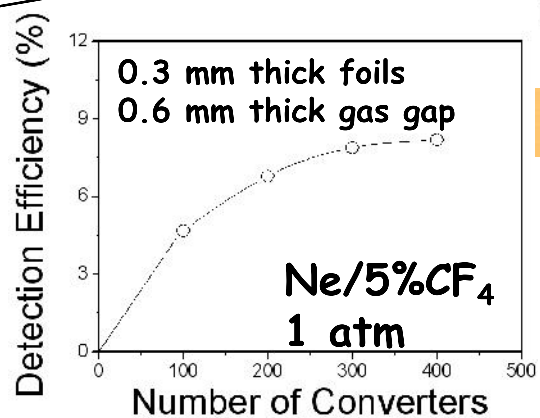


Detector design:

- -) Foils composition (Neutron)
- -) Foils thickness (2.5 MeV)
- -) Gas gap thickness (Deposited Energy)
- -) Converter height (e- Diffusion)
- -) Number of foils (Detector Length)

Detector Performances:

- -) Spatial Resolution
- -) Detector Efficiency



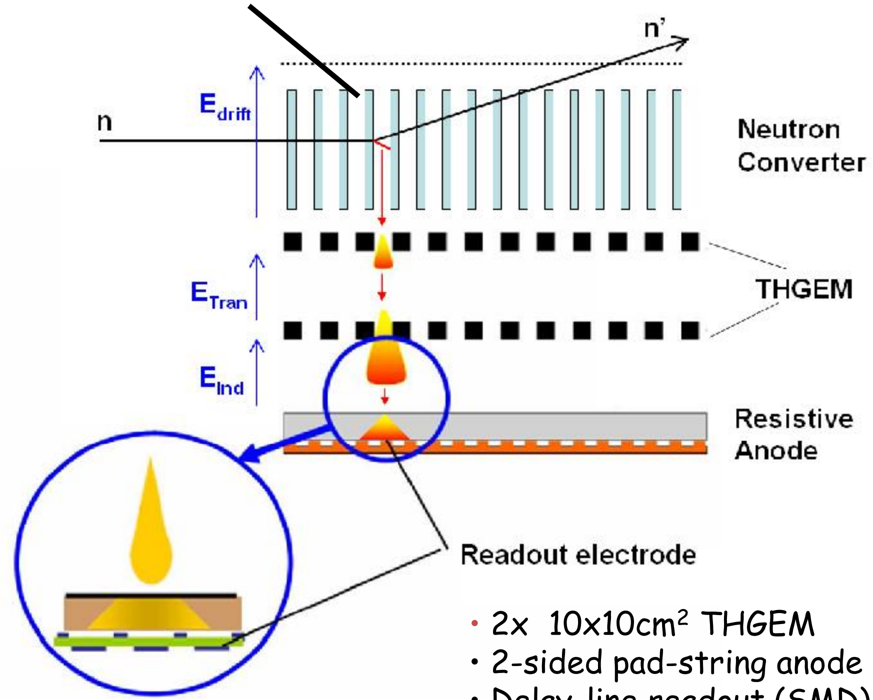
300 foils ➔ %8 efficiency

Cortesi et al. 2013 JINST 8 P01016

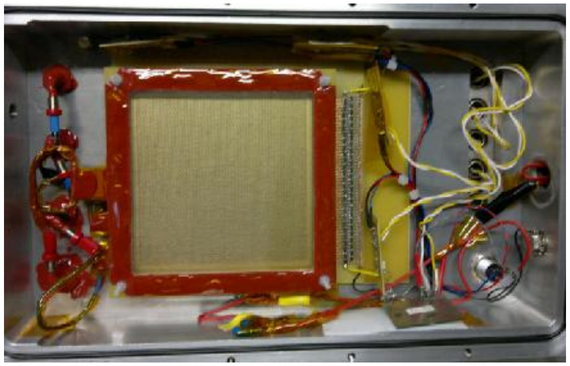
10x10 cm² Detector Prototypes

Produced using 3D printing technologies
Foils thickness = 0.6/1.2 mm
Gas gap = 0.6 mm
Height = 6 - 10 mm
Material → Antistatic ABS

Antistatic HDPE layers
(no charging up)



- 2x 10x10cm² THGEM
- 2-sided pad-string anode
- Delay-line readout (SMD)



Studies:

-) Electron Transport Efficiency

-) Imaging Capability

Cortesi et al. 2013 JINST 8 P01016

Detection Efficiency (First test)

PTB Neutron Facilities (GERMANY)
2.5 MeV, 14 MeV, Broad spectrum (< 18 MeV)

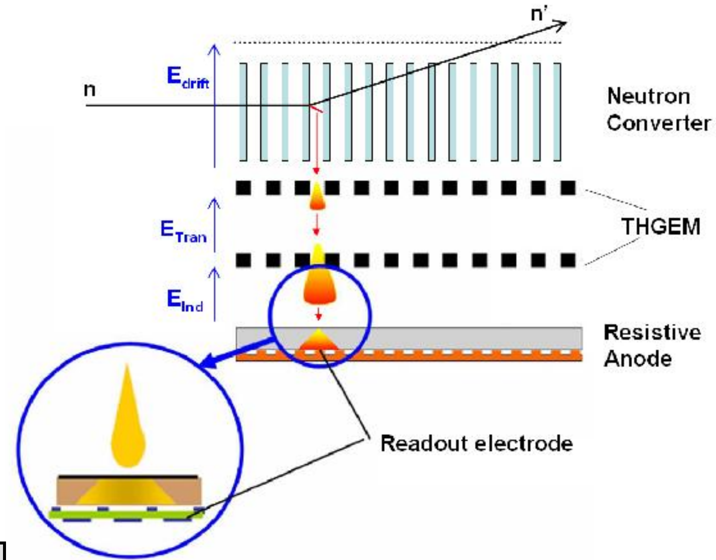
14 MeV Neutrons

Converter (0.6 mm gas gap)	*Detec. Effic.*
83 foils 0.6 mm thick	2% (0.2%) ➔ 7%
55 foils 1.2 mm thick	3.8% (0.2%) ➔ 6.7%

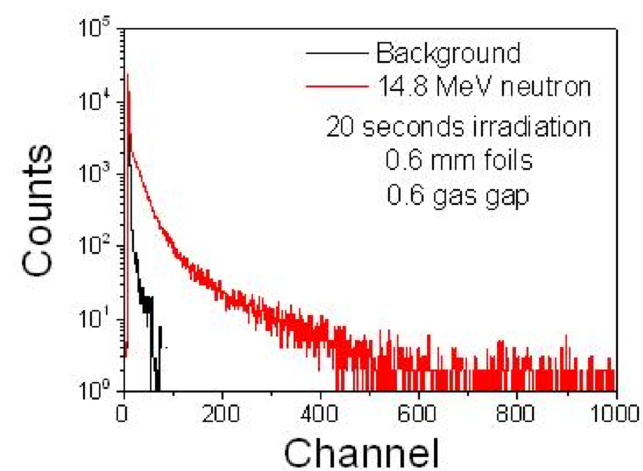
2.5 MeV Neutrons

Converter (0.6 mm gas gap)	*Detec. Effic.*
83 foils 0.6 mm thick	0.62% (0.01%) ➔ 1.87%
55 foils 1.2 mm thick	0.22% (0.015%) ➔ 1.13%

Measured With MCA — **Measured with DAQ** — **Calculated**



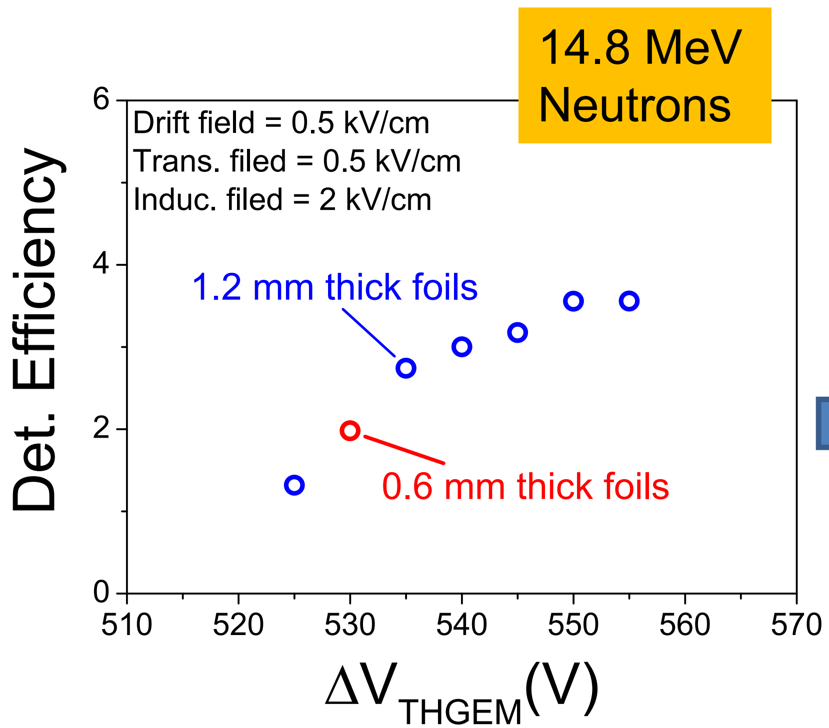
Typical Pulse-height distribution (14.8 MeV) measured from 2nd THGEM
➔ Large Dynamic Range
➔ Low pulse-height threshold

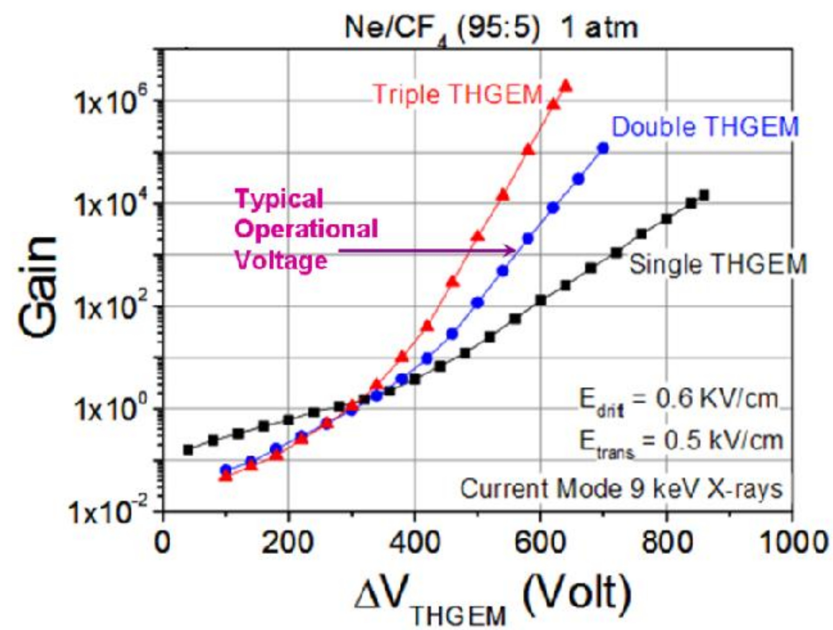


Problems:
- -) lower e- transport efficiency (diffusion – charging up)
- -) lower H in the antistatic-ABS
- -) Electronic discrimination Threshold

Detection Efficiency vs. Gain

Detection Efficiency ➔ -) n energy ➔ Converter geometry / Composition
-) **Detector Gain** ←→ **Electronic Noise**
-) e- transport efficiency in the small gas gap

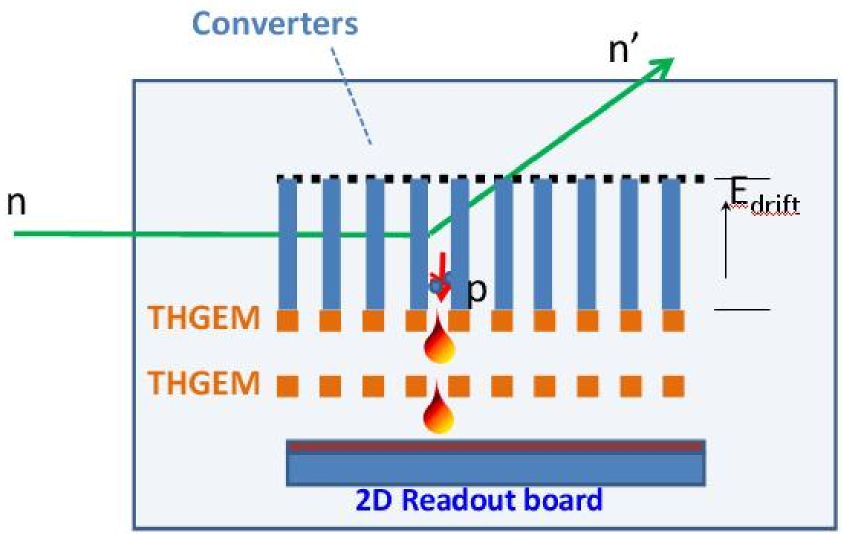


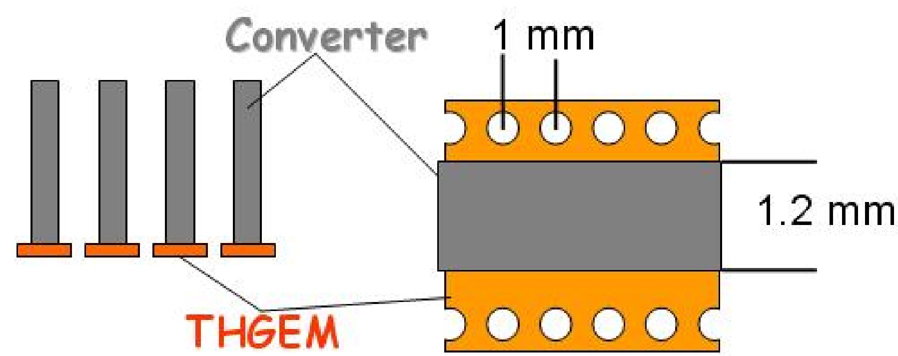


Small variation of Gain ➔ Large variation of the Detection efficiency

Detection Efficiency (new setup)

Gas gap pitch = THGEM hole pitch





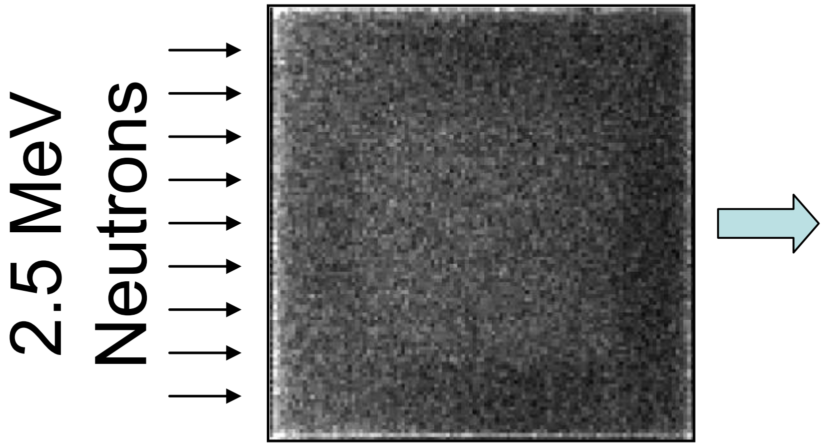
2.5 MeV Neutrons

Converter (0.6 mm gas gap)	*Detec. Effic.*
55 foils 1.2 mm thick	0.78% ➔ 1.13%

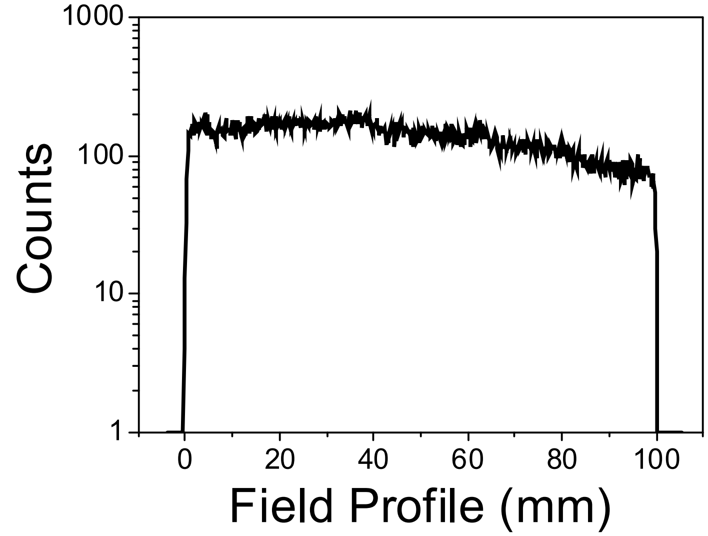
Higher Max Detection Efficiency (0.78%) compared to the "standard" configuration (0.22%) due to better focusing of ionization electrons into the THGEM holes!

Detector Response: Homogeneity

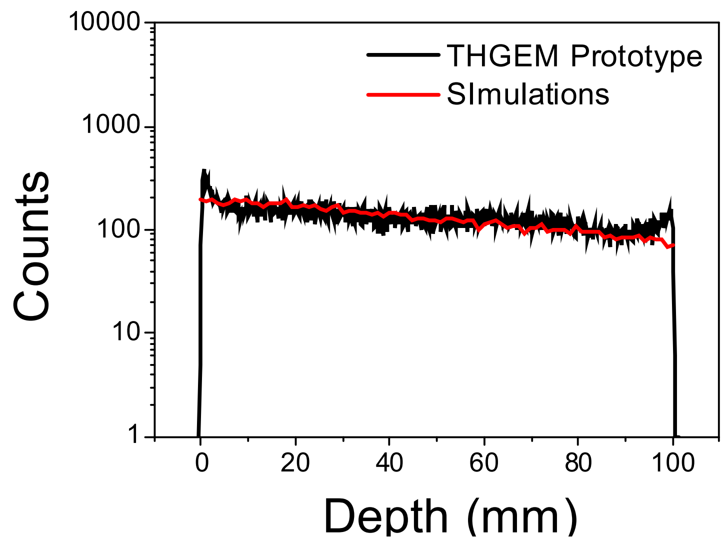
83 foils 0.6 mm thick



"Beam Profile"



"Beam Attenuation"

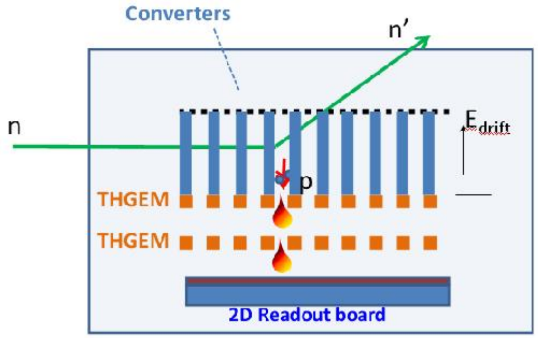


Good homogeneity of the detector response (gain variation)

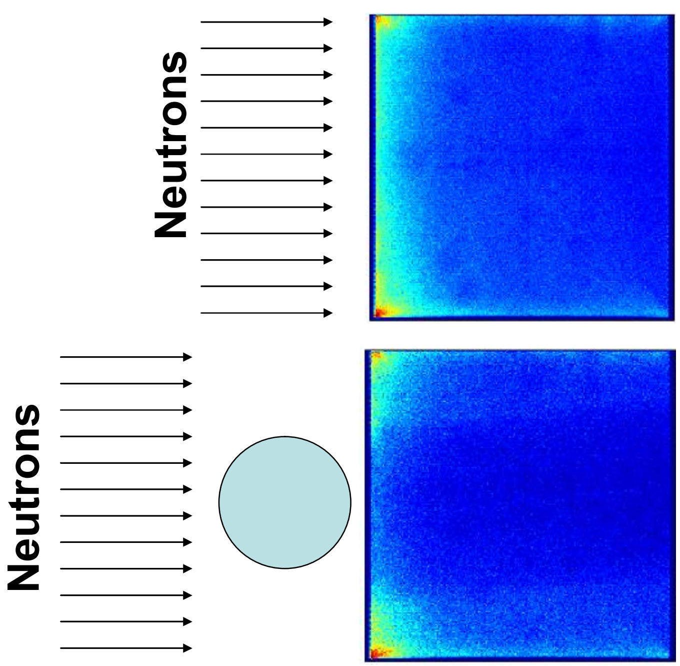
➔Field-Flat Correction

Fast-Neutron Imaging (new setup)

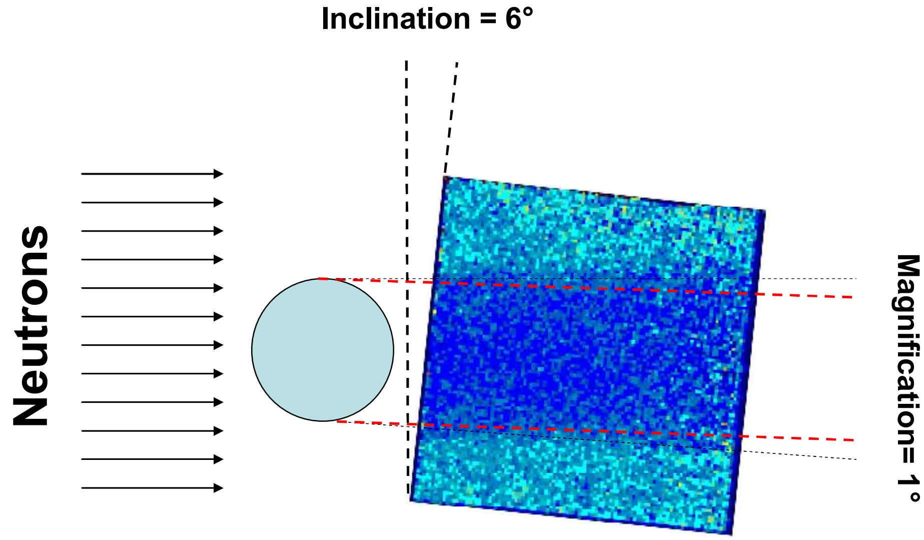
83 foils 0.6 mm thick



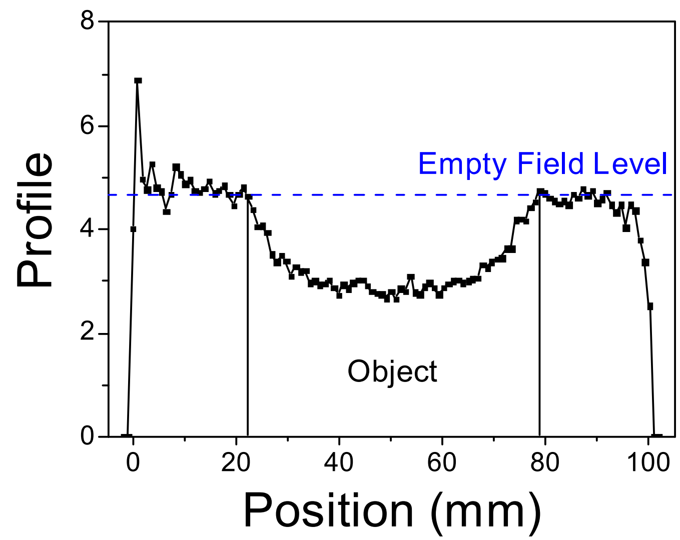
Raw Images



Flat-Field Correction

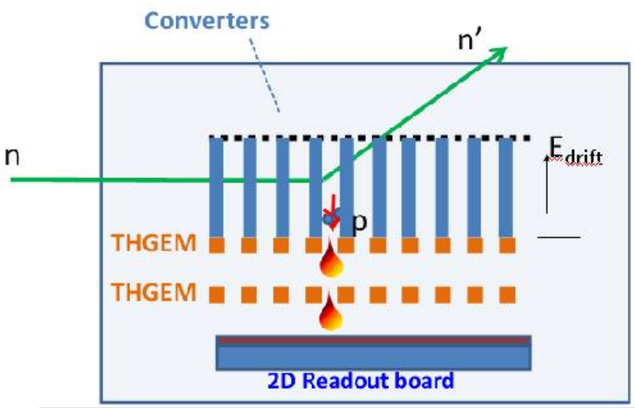


Projection

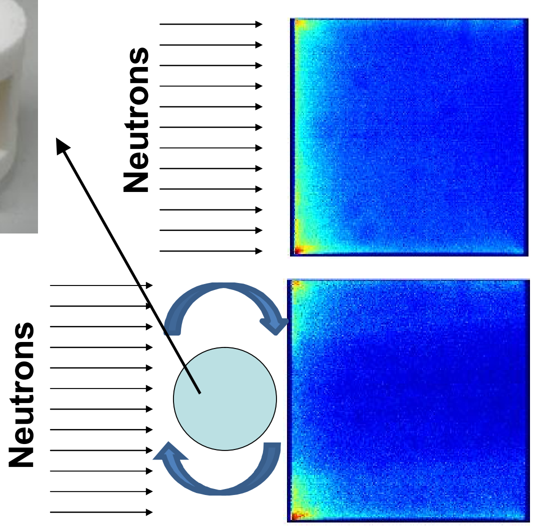


Fast-Neutron Tomography

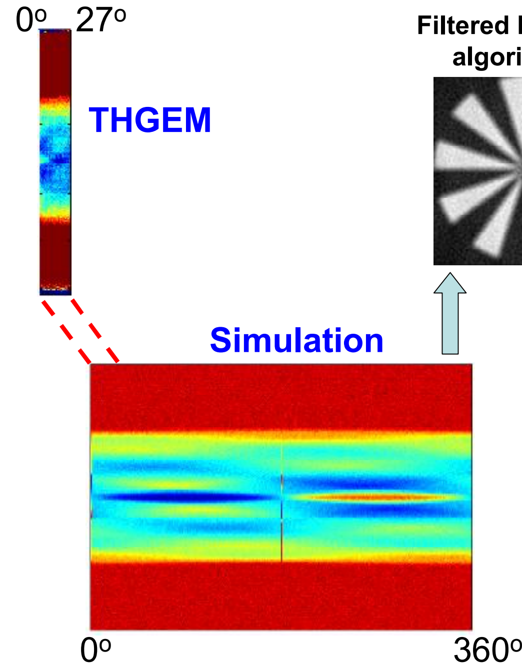
Stable operation at a gain of 10^3

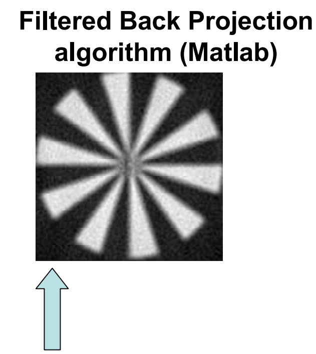


Broad Neutron Spectrum (< 18 MeV)



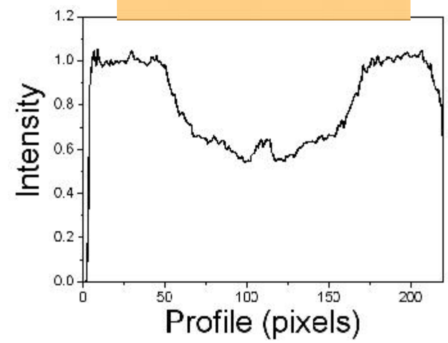
Incomplete scan due to fail of the accelerator!



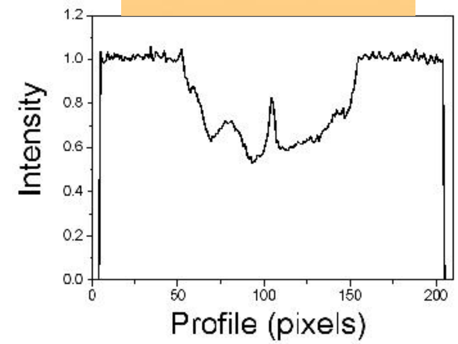


2.5 MeV Neutron
Ideal Detector
(No crosstalk!)

Measured



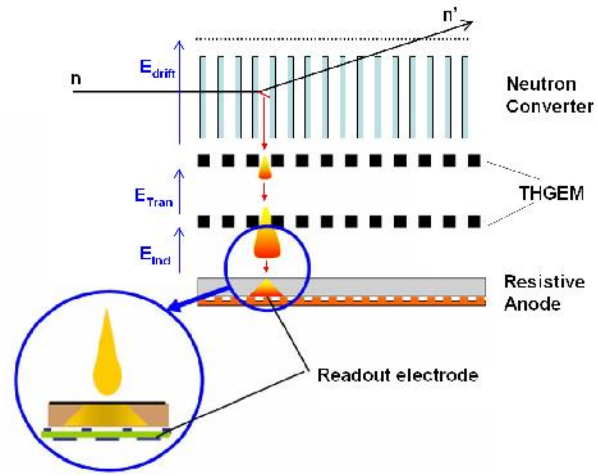
Simulated

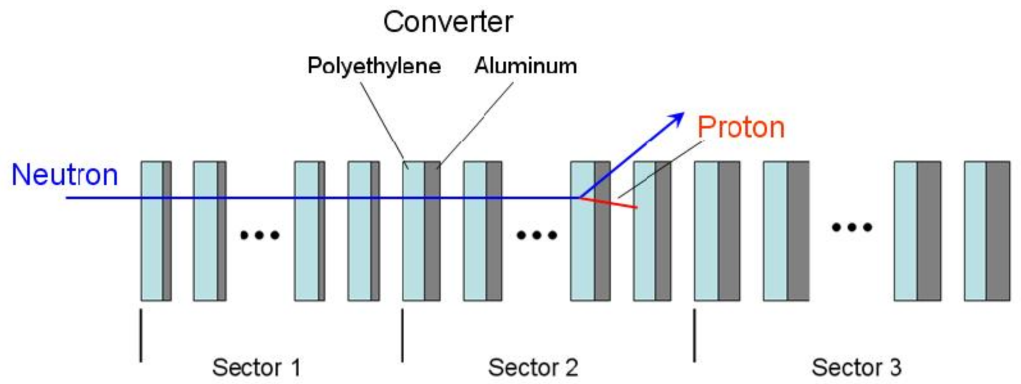


Measured Sinogram shows Similar Structures observed in the simulated one!

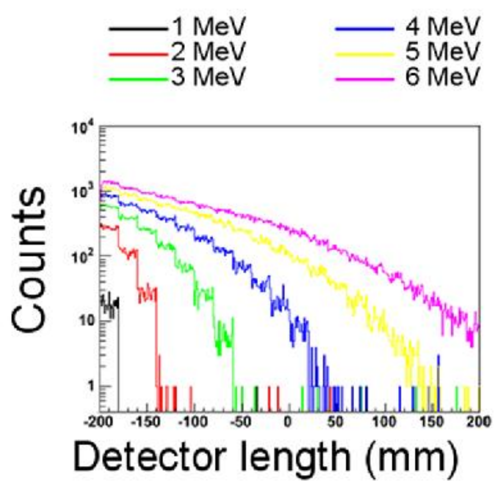
Energy-Selective Fast-Neutron Imaging Detector

Idea: various energy-selective stacks of many radiator foils + Charge readout



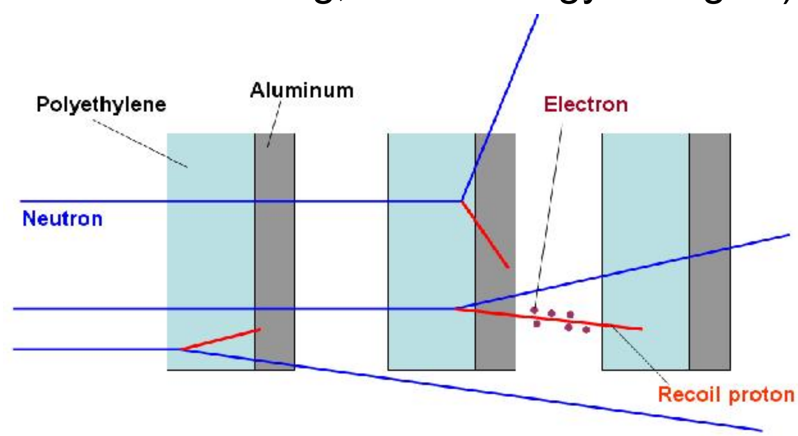


Energy-selective coating ➔
protons are slowed down or absorbed (thickness of the energy selective coating, recoil energy & angles)



Detector Response!

Example (Simulation):
six E-selective stacks,
Sensitivity = 1-6 MeV



Main Application: monitoring, and characterization of special nuclear materials (i.e. nuclear safeguard), detection of neutron streaming and material activation in power plants

Summary & Future Plan

Goal ➔ Study of Thermal-Hydraulic Phenomena

Cold-/Fast- neutron tomographic ➔ 2D cross-sectional images
Main Application: Multi-phase flow for R&D Nuclear plan technologies
Others: Detection of SNM, ...

Detector technologies ➔ Feasibility study + Small Prototype + Test
Gaseous Detector (THGEM-GEM)

Fast neutron Tomography

New Idea: many n-to-p converters, single 2D Detector readout
* Expected detection efficiency ~7% (300 foils, 2.5 MeV neutrons)
* 1D Radiography, spatial resolution ~ 1 mm

TWO-FAST
Improvement of charge-readout electronics
Better production technique for the converter
New test beam at PTB for tomography reconstruction

COLD NEUTRON
30x30 cm^2 ^{10}B-GEM detector prototype + High counting rate electronics

PROTON RADIOGRAPHY
First test with THGEM prototype → Next test with better electronics and setup

E-SELECTIVE FAST NEUTRON IMAGING
New idea ➔ Nuclear waste characterization & neutron streaming/material activation in power plants