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Wir schaffen Wissen – heute für morgen

Progress in Fast-Neutron THGEM Detector for Fan-Beam Tomography Applications

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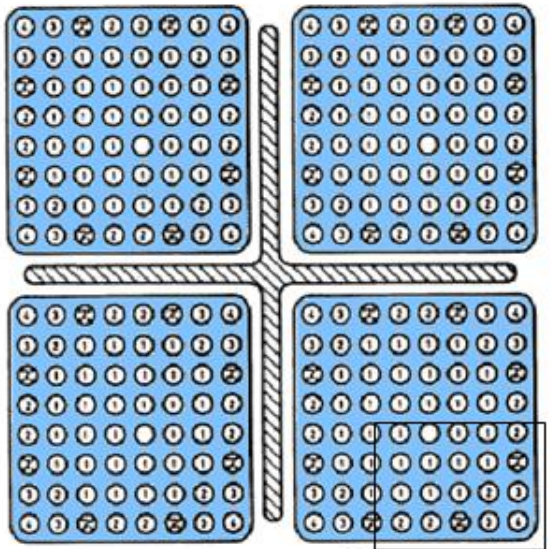
10th RD51 Collaboration Meeting, Stony Brook University, USA

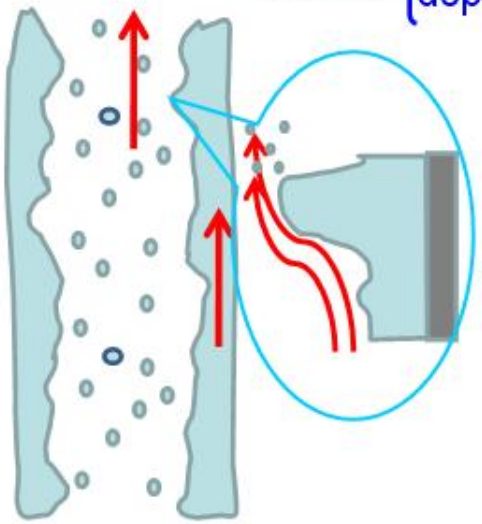
Fluid dynamic studies in BWR Fuel Rod Bundles

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

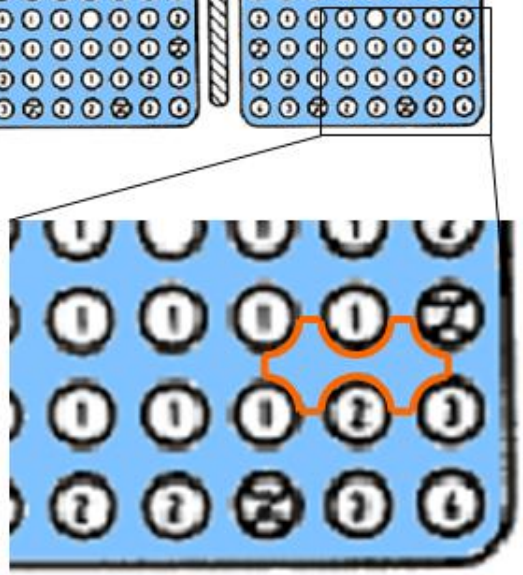


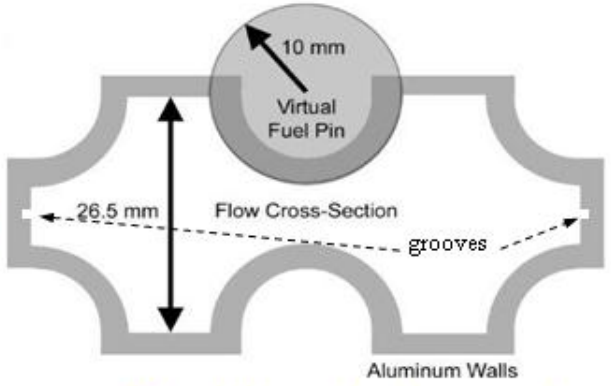
Flow regime: Wavy annular flow:

droplet { entrainment / deposition



Dry out!

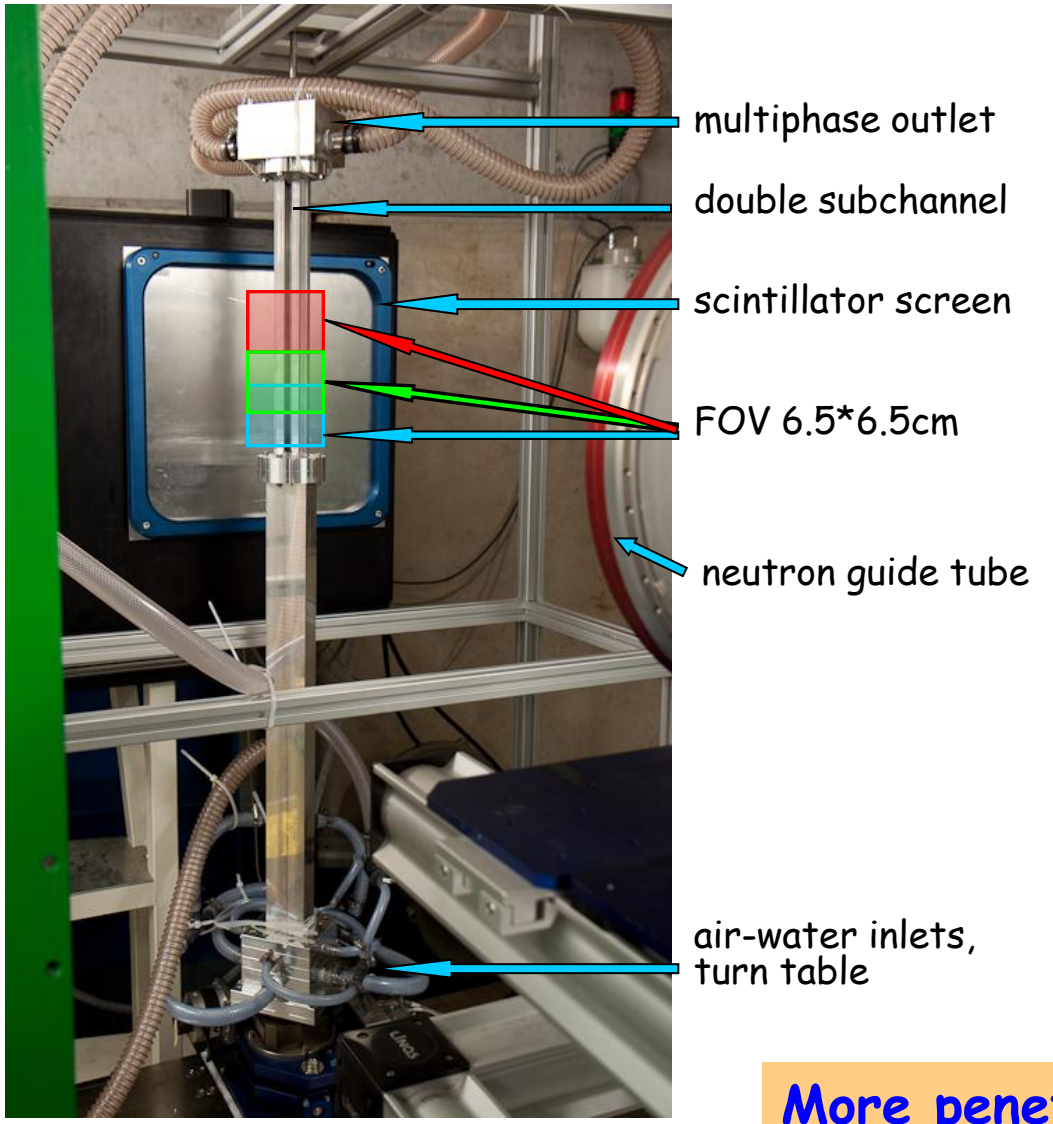




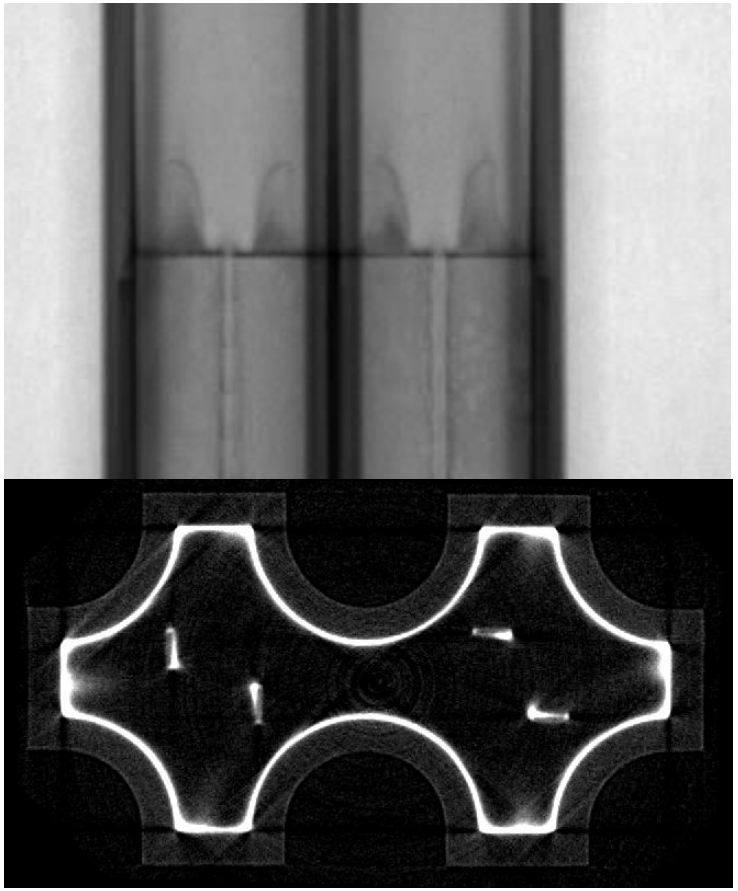
Double subchannel

Example: Imaging using cold neutrons

ICON beam line, SINQ at PSI, Switzerland: (Zboray et al. Nucl. Eng. Des. 241 pp.3201)



Double subchannel + spacer inside:

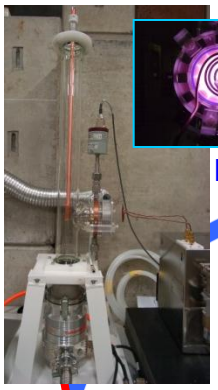


More penetration depth → Fast Neutron

Goal: Fast-Neutron Tomography

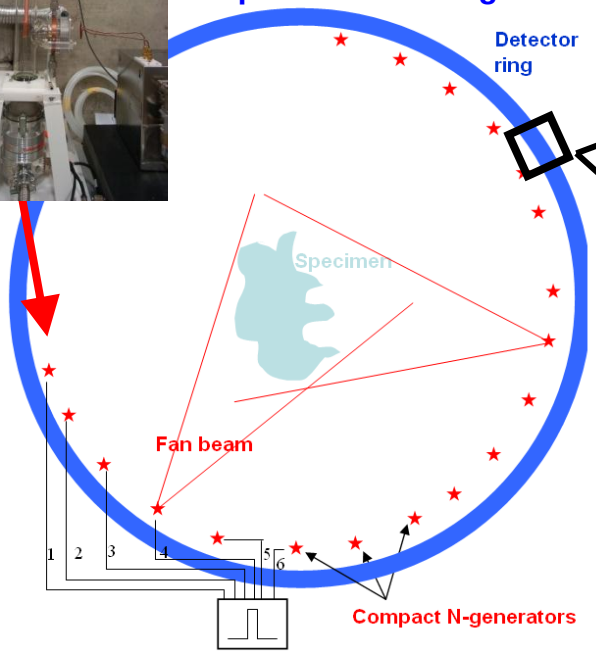
TwoFast Project:
- Multiple fast-n point sources (e.g. D-D fusion, 2.5 MeV)
- Ring-shaped Fast-Neutron detector

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)



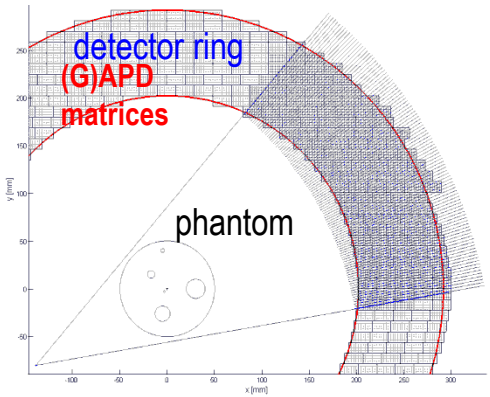
RF-driven Plasma ion source

D-D pulsed neutron generator



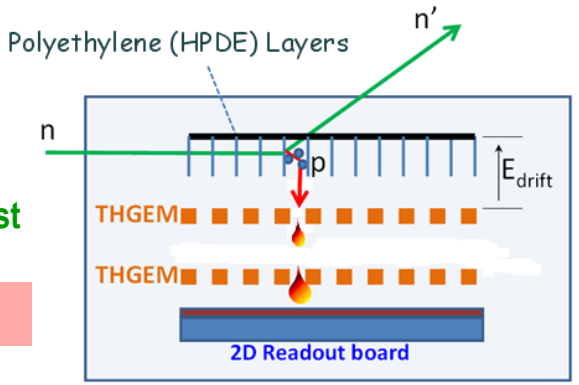
Multiple point source sequentially pulse

Plastic scintillator +(G)APD matrix



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

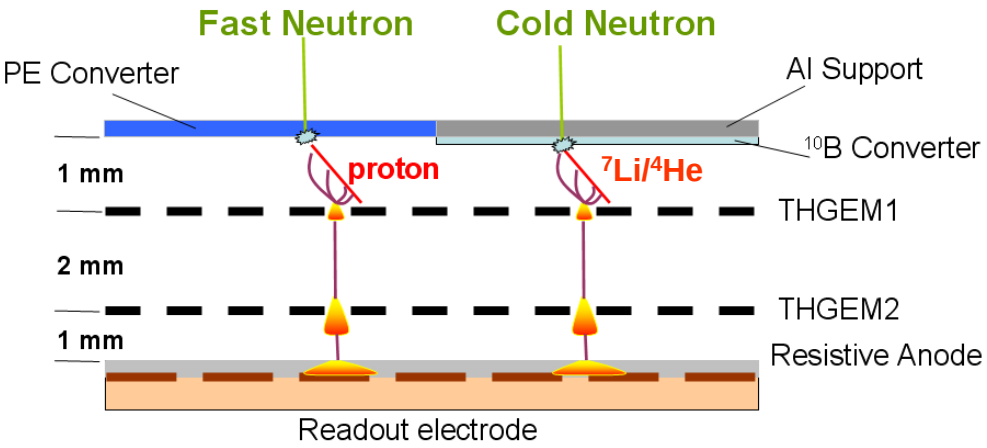
In this presentation



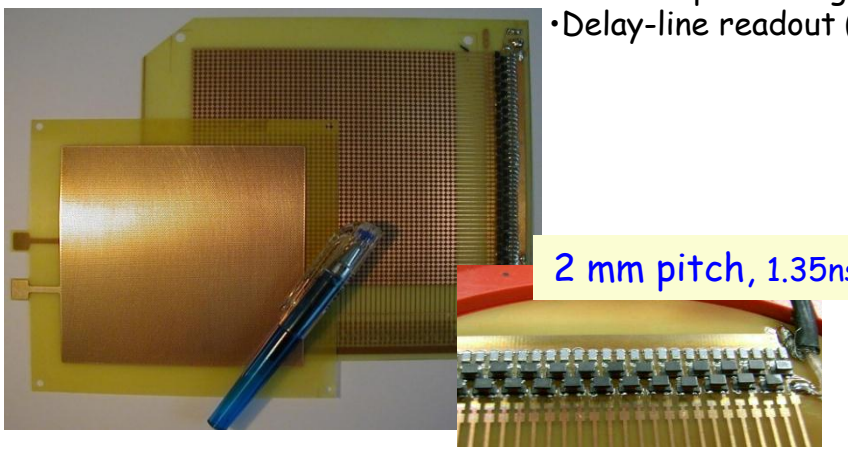
1D High-Efficiency Fast-Neutron Imaging Detector

2D Imaging with neutrons

Fast/Cold Neutron 2D radiography

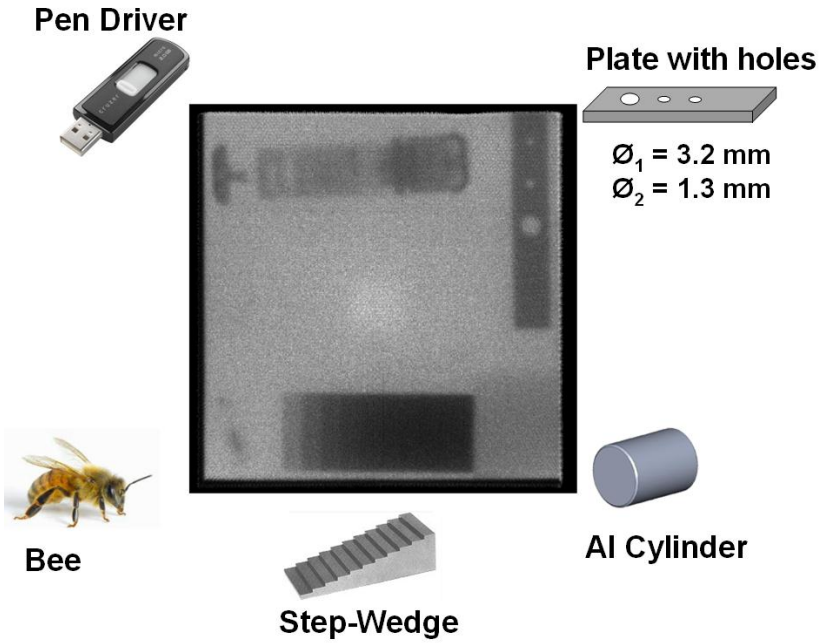


- 2x 10x10cm² THGEM
- 2-sided pad-string anode
- Delay-line readout (SMD)



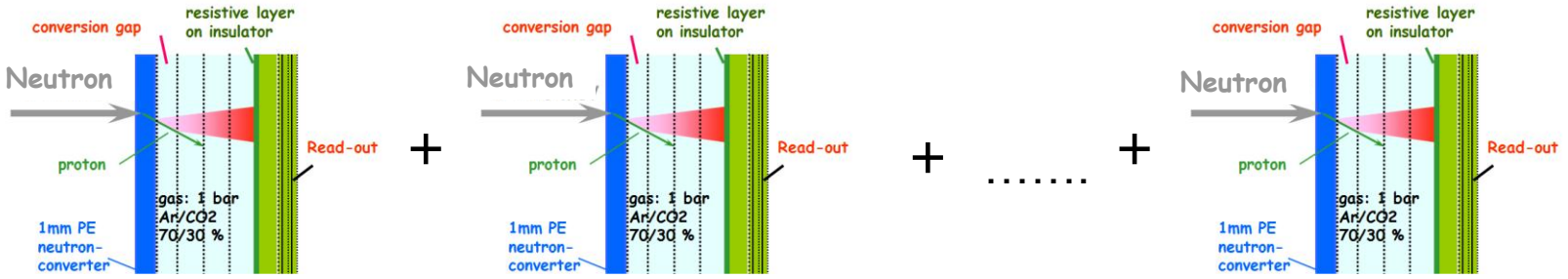
Ionization electrons are multiplied & localized in cascaded-THGEMs imaging detector.

-) Detection efficiency: < 0.1%(fast-n)
~ 5% (cold-n)
-) Spatial Resolution ~ 1 mm
-) Counting Rate ~ 1 kcps/cm²

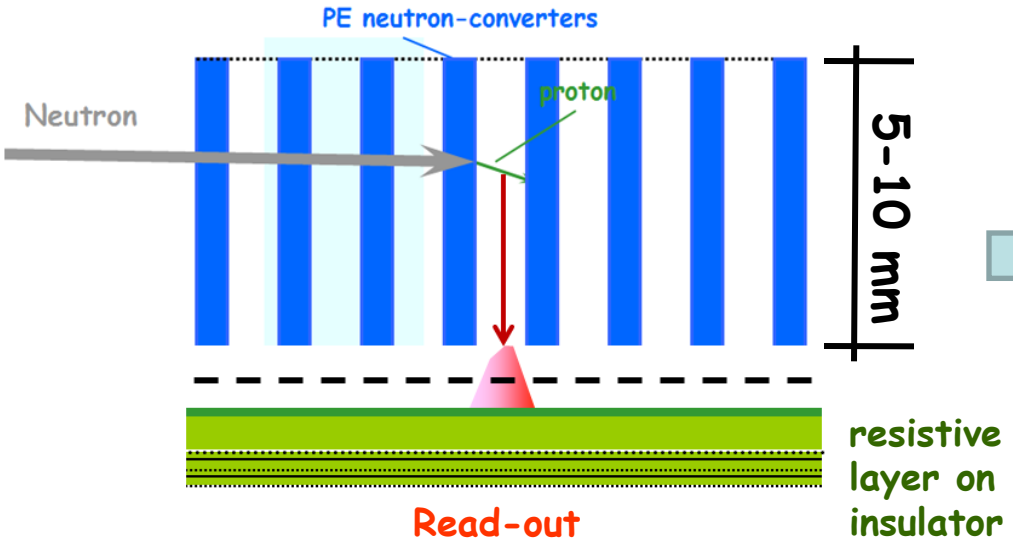


High Efficiency Detector

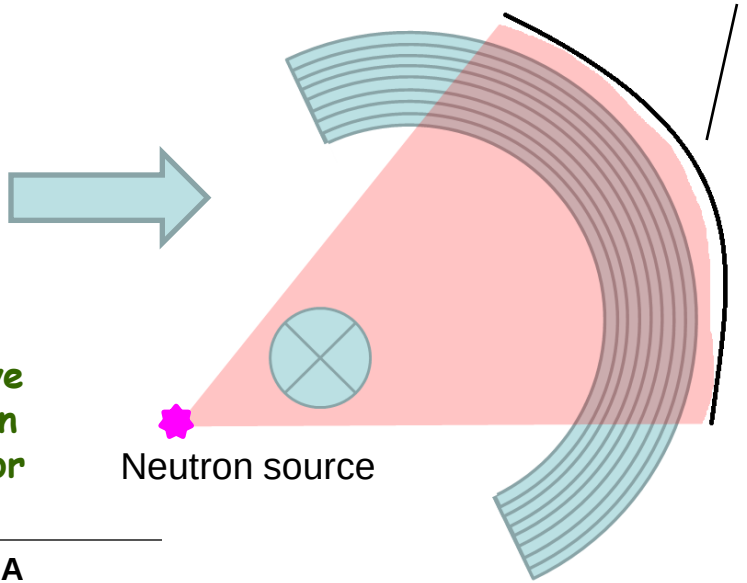
2D radiography: for efficiency ➔ need to cascade many detectors!
100 detector elements for efficiency ≈ 6%



1D radiography ➔ 2D cross-sectional tomography
1 detector for efficiency ≈ 10%



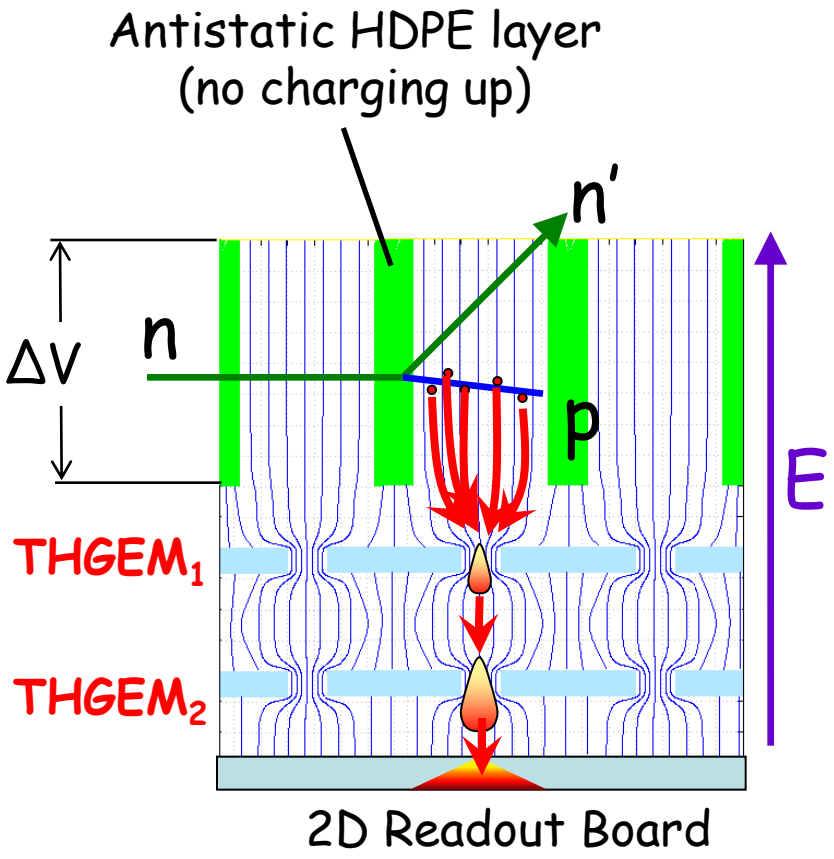
Projectional image ➔ 1D distribution of neutron attenuation inside the object, integrated over projection chords



Multi-layer converter + THGEM detector

Detector Concept:

- 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.



Detector design:

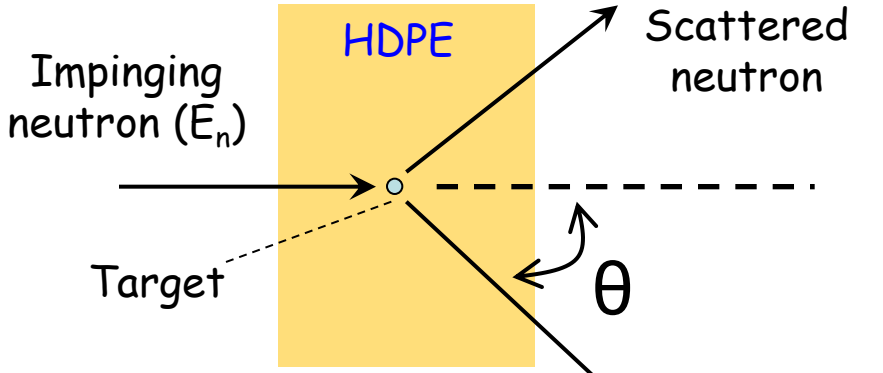
-) Foils thickness (2.5 MeV neutron)
-) Gas gap thickness (Deposited Energy)
-) Converter height (Axial resolution)
-) Number of converter foils (Detector Length)

Detector Performances:

-) Spatial Resolution
-) Efficiency of transport e- in small gap
-) Detector Efficiency

Cortesi et al. 20012 *JINST 7 C02056*

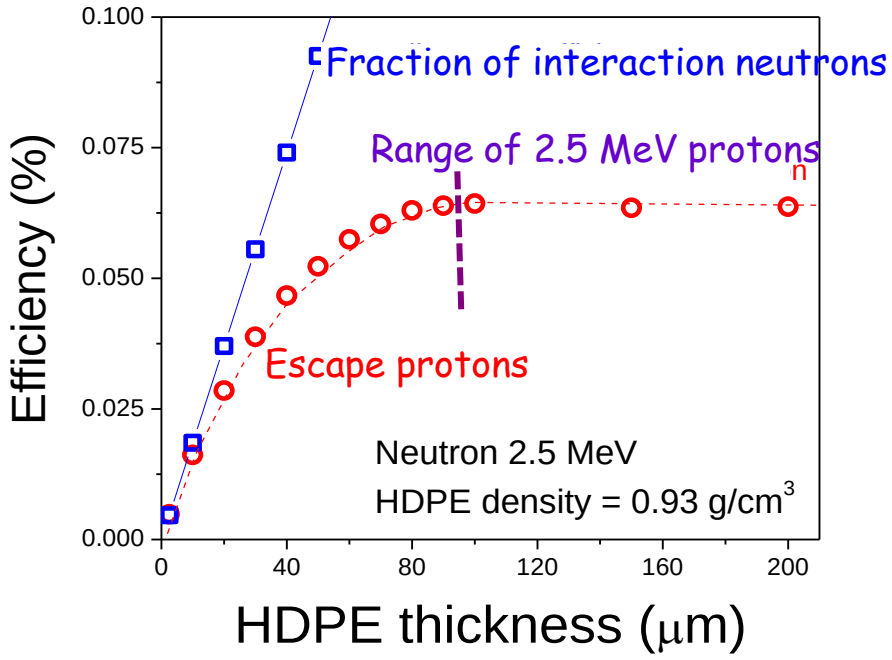
Simulation ➔ Converter Thickness



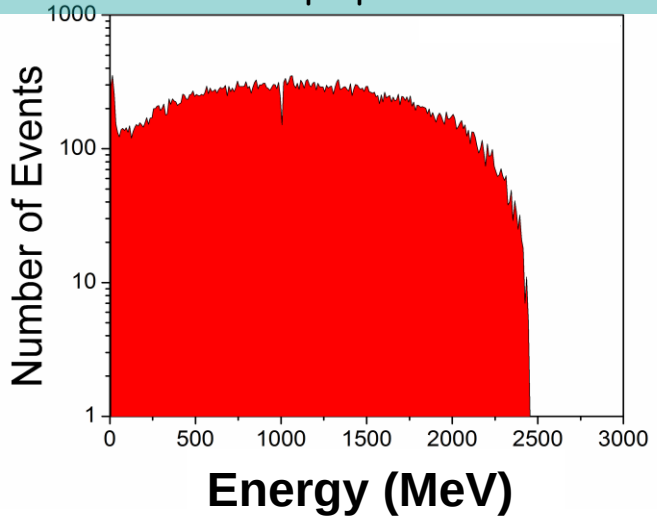
$$\frac{E_R}{E_n} = \frac{4A}{(1+A)^2}\cos^2(\theta)$$

HDPE (C_2H_4 - Mass Density = 0.93 g/cm^3)

Target	Max. Ener. Tran.	σ(2.45 MeV)
^1H	100% → 2.5 MeV	~2.55 b
^{12}C	28.4% → 0.7 MeV	~1.6 b



MCNP calculated energy spectrum of escape protons



For 2.45 MeV Neutron impinging on HDPE layer:

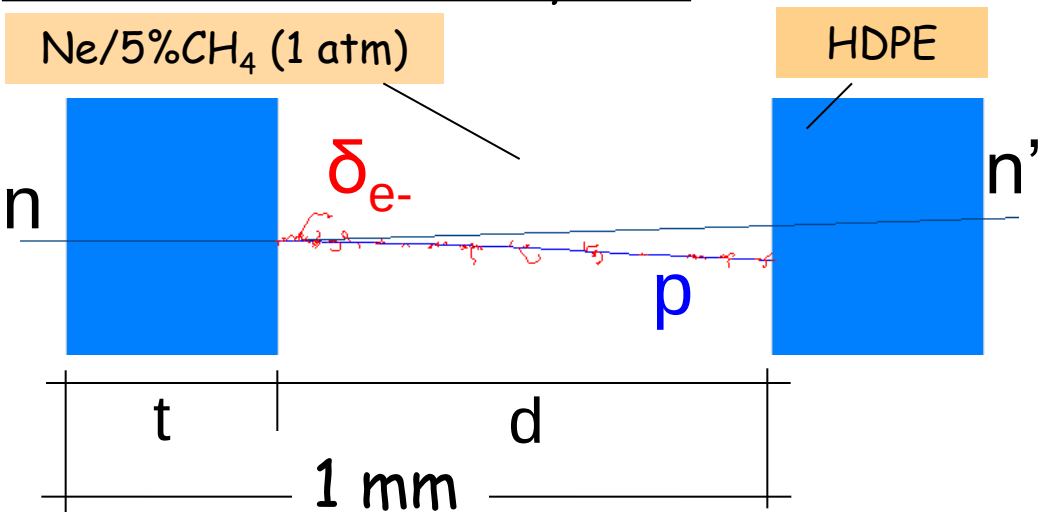
-) Max. Efficiency ≈ 0.06%

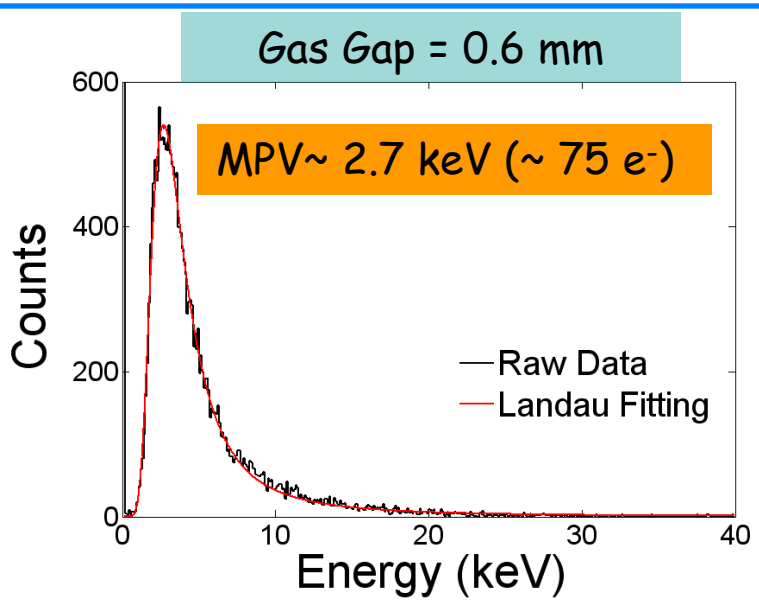
-) Effective Conversion length = 100 μm

-) Broad Spectrum (0 → 2.5 MeV)

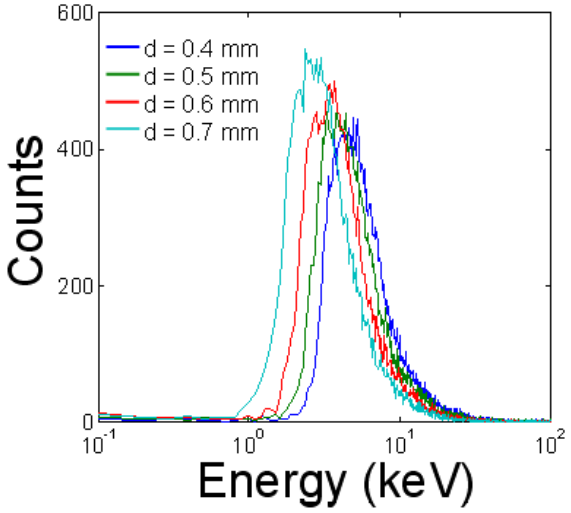
Simulation ➔ Deposited Energy in the Gas

Geant4 Simulation snapshot





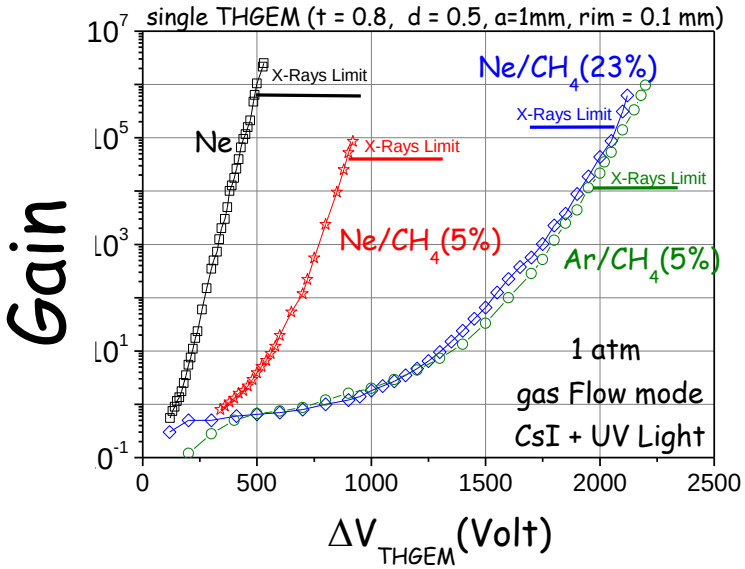
Deposited Energy Vs. d (gas gap)



Broad Spectrum of Energy deposited by recoil proton

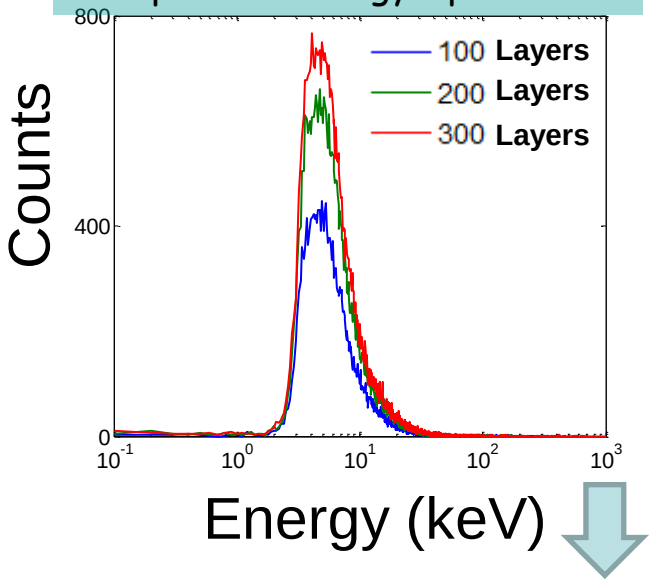
Larger dynamic range in Ne-Mixtures

Cortesi et al. 2009 *JINST* 4 P08001

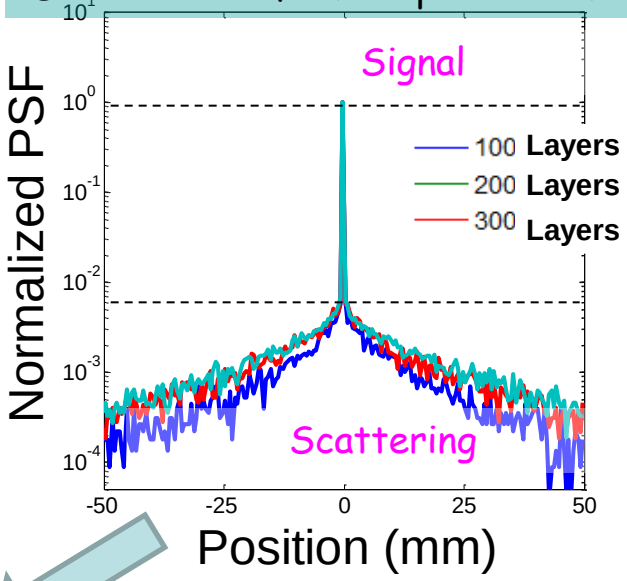


Simulations ➔ Efficiency & Resolution

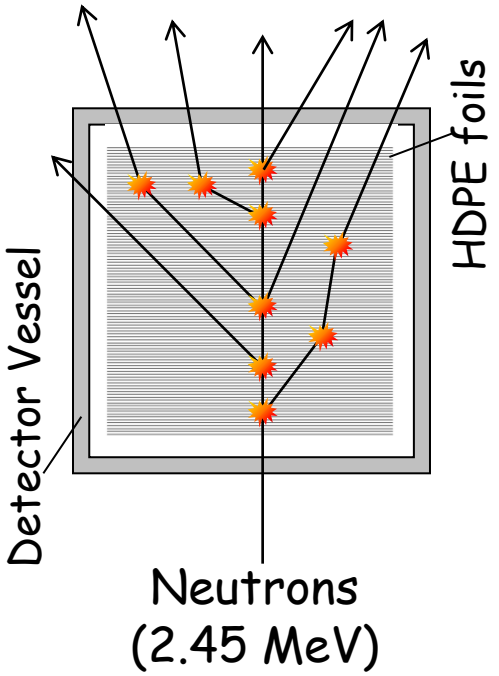
Deposited Energy Spectrum



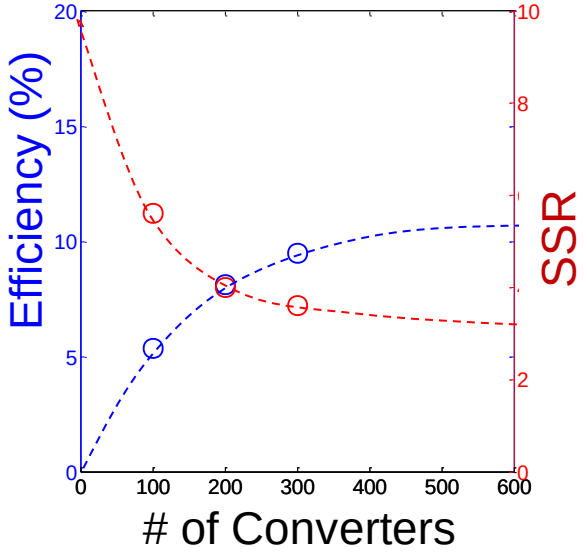
Distribution of the deposited charge



Parameters
-) HDPE Thickness = 0.4 mm
-) Gas Gap = 0.6 mm



SSR = Signal-to-Scattering ratio

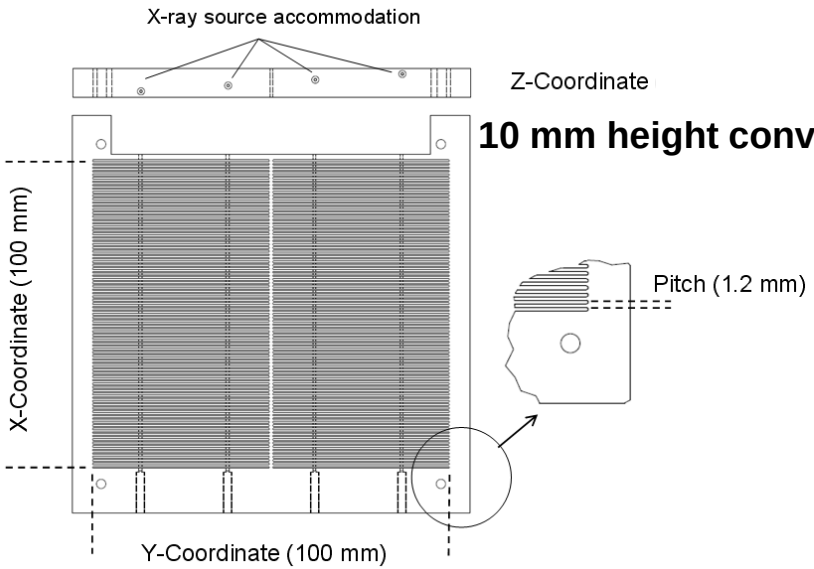


Cost effective solution: 300 HDPE layer
Conversion Efficiency ➔ ~8%

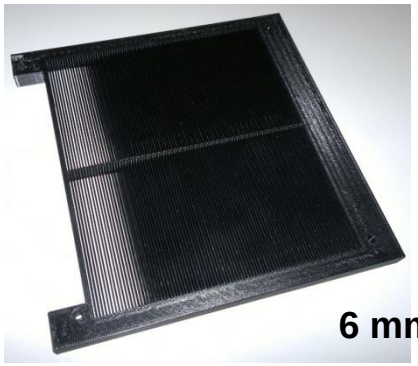
Cortesi et al. 20012 *JINST 7 C02056*

Converter Prototypes

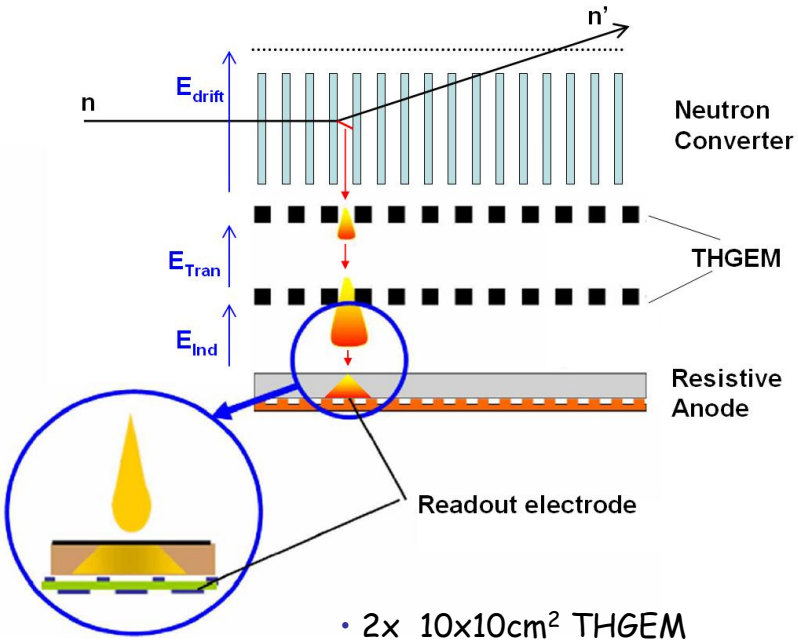
Produced using 3D printing technologies
Foils thickness = Gas gap = 0.6 mm
Height = 6 mm, 10 mm
Material → Antistatic ABS



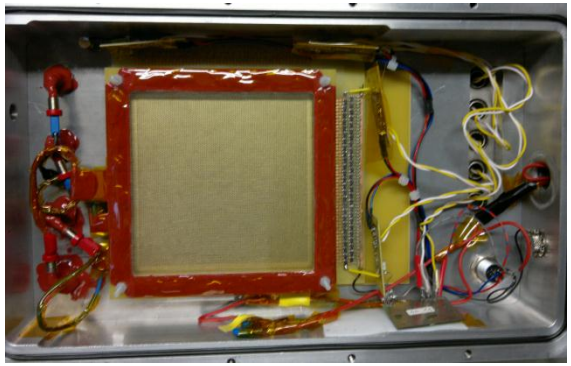
10 mm height converter



6 mm height converter

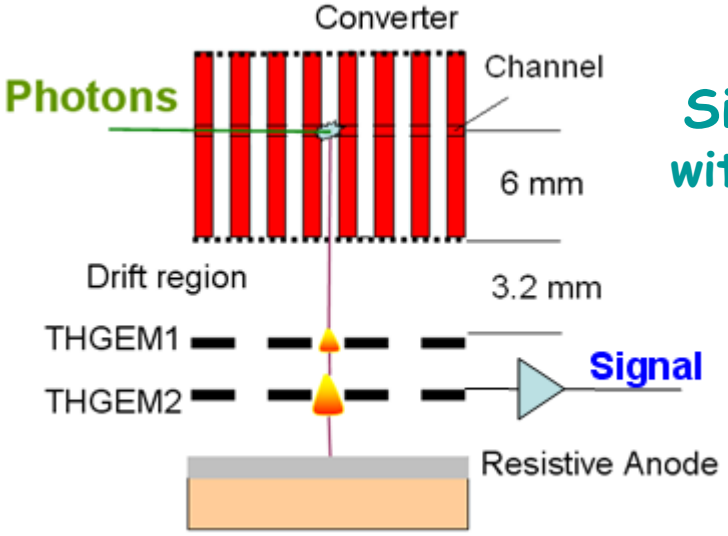


- 2x 10x10cm² THGEM
- 2-sided pad-string anode
- Delay-line readout (SMD)

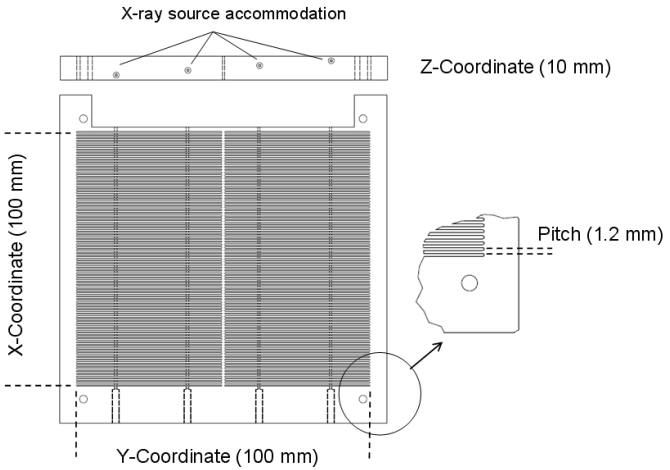


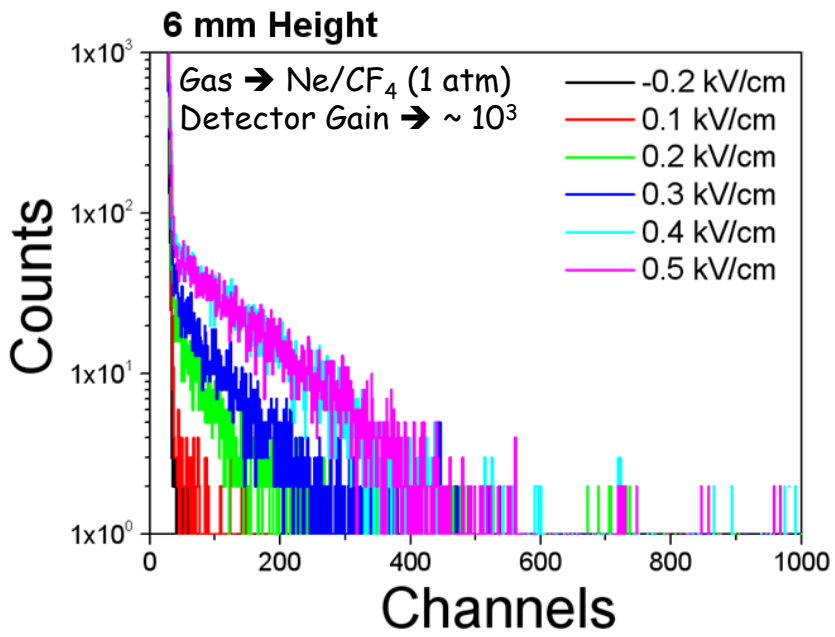
Cortesi et al. 2007 JINST 2 P09002

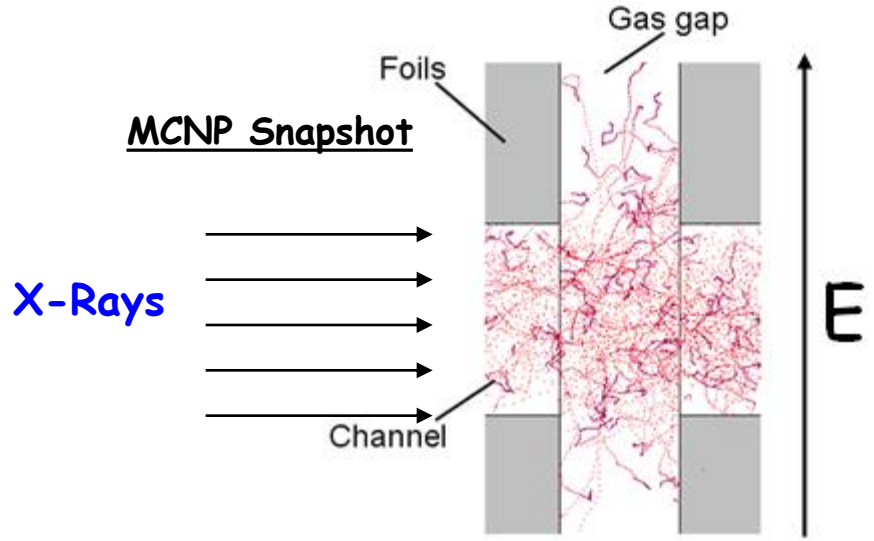
e⁻ Collection Efficiency Vs Electric Field



Side-Irradiation with soft (5.9 keV) X-Rays





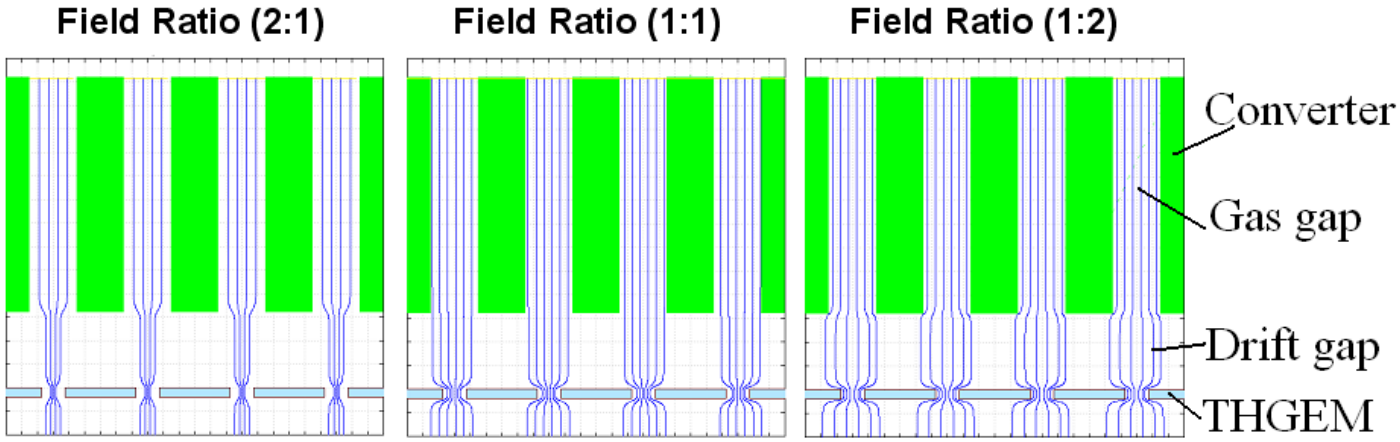


Full Collection efficiency above 0.4 kV/cm in the Converter Gas Gap

Electric Fields (Converter-Drift) Tuning

Focusing of the ionization electron transferred from the converter Gas Gap to the Drift Gap (THGEM hole pitch ≠ Converter Foils pitch ➔ Drift Gap)

Field Ratio = Drift / Converter

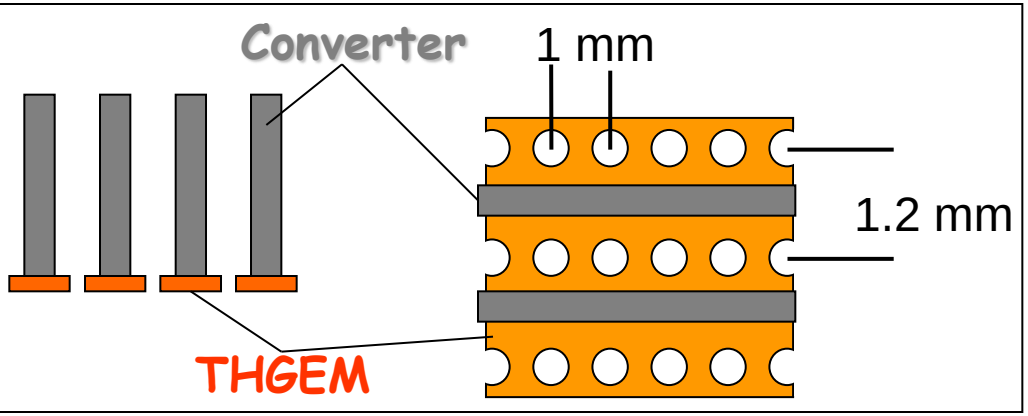


Full transfer efficiency for field ratio > 2:1

Ideal values: (1kV/cm Drift Field, 0.5 kV/cm Converter Field)

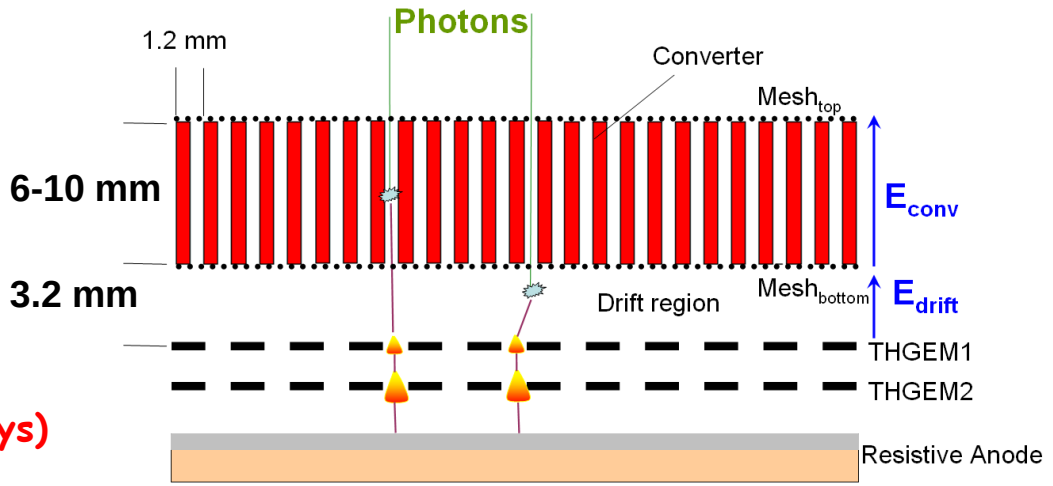
NEXT

New THGEM Configuration
hole pitch = Foils pitch
(No drift Gap)



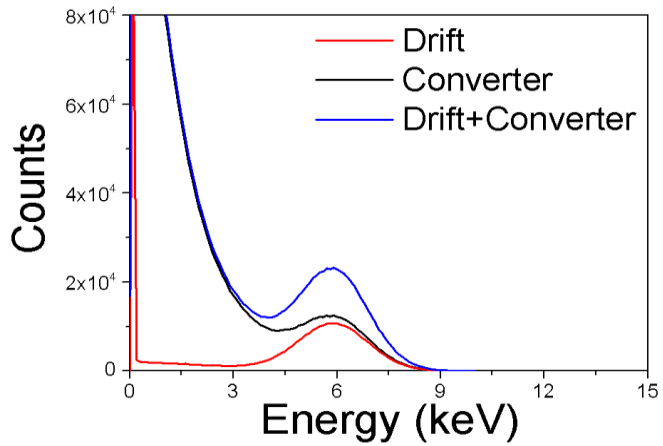
Electron Transport through the (0.6 mm) gas gap

2-cascade THGEM Detector:
-) Effective area 10x10 cm
Converter Prototypes geometry:
-) Foils Thickness = 0.6 mm
-) Gas Gap = 0.6 mm
-) Converter Height = 6mm / 10 mm
-) number of foils = 83



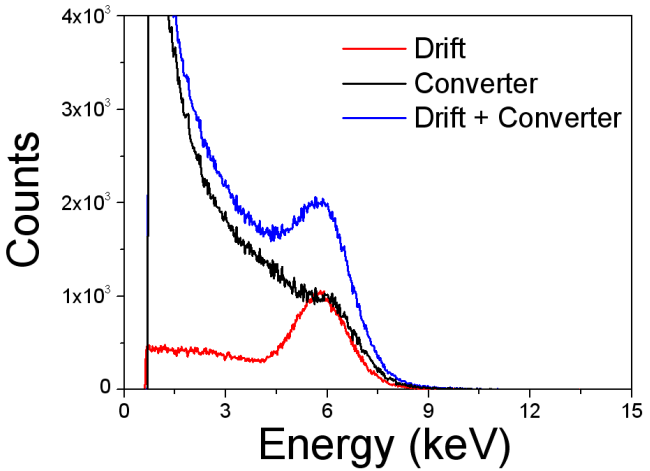
Transport efficiency - Methodology:
-) "Top" irradiation with soft (5.9 keV X-rays)
-) Comparison between the spectra of Deposited Energy (MCNP) and measured Pulse-Height Spectra using the THGEM detector

MCNP calculated spectra of deposited energy



6 mm height Converter

Measured Spectra



Electron Transport through the (0.6 mm) gas gap

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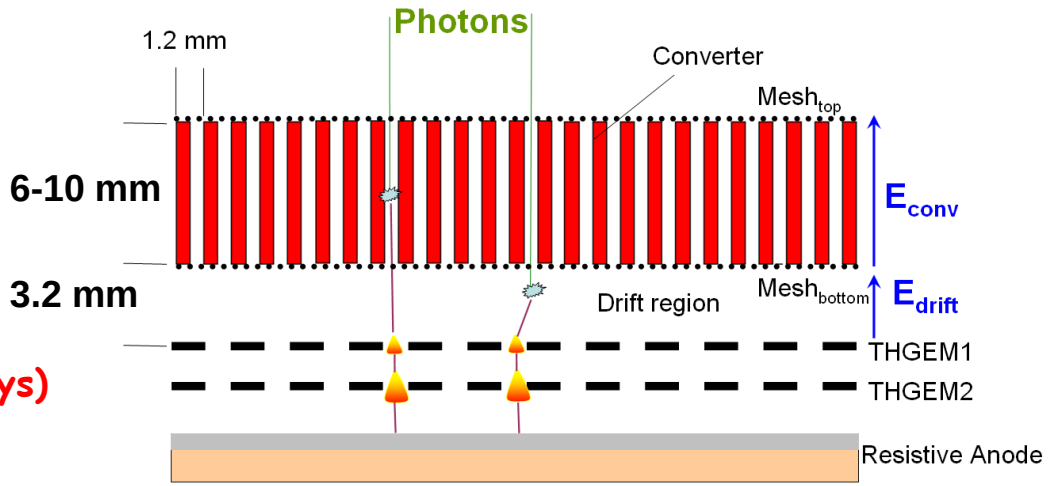
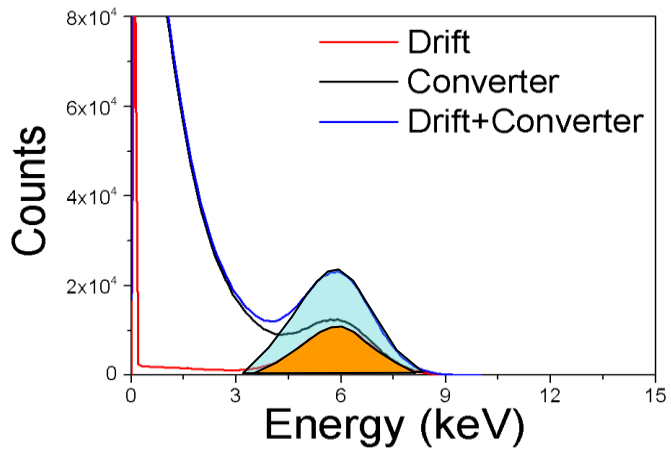


Transport efficiency - Methodology:
-) "Top" irradiation with soft (5.9 keV X-rays)
-) Comparison between the spectra of Deposited Energy (MCNP) and measured Pulse-Height Spectra using the THGEM detector

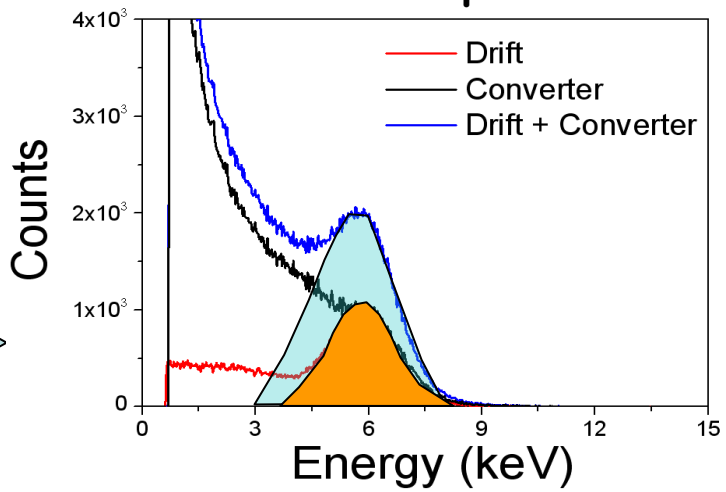
Electron Transport Efficiency ➔
Converter-to-Drift Counts Rate ratios = MCNP/Measured (full efficiency = 1)

MCNP calculated spectra of deposited energy



6 mm height Converter

Measured Spectra

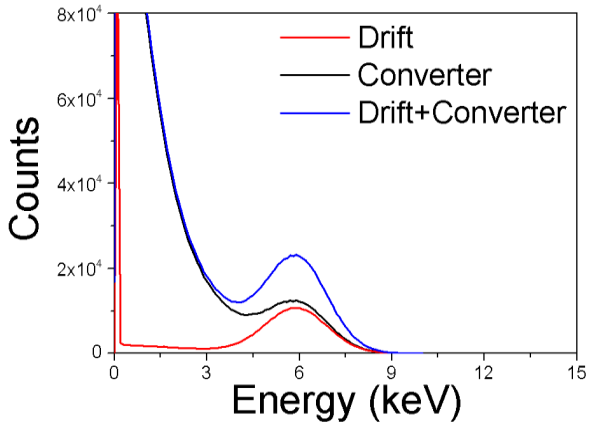


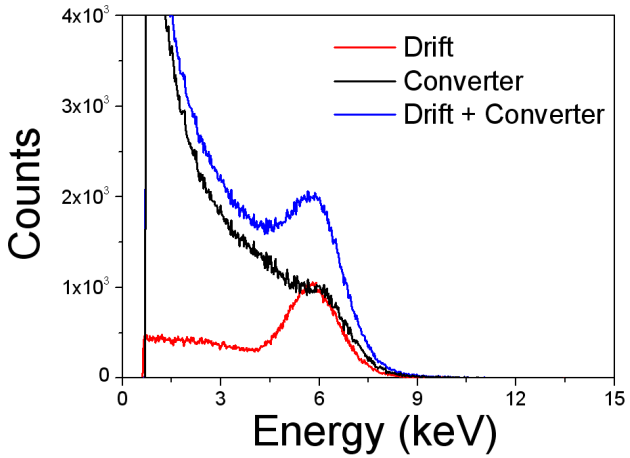
Electron Transport through the (0.6 mm) gas gap

Deposited Energy (MCNP)

Measured Spectra

6 mm height Converter

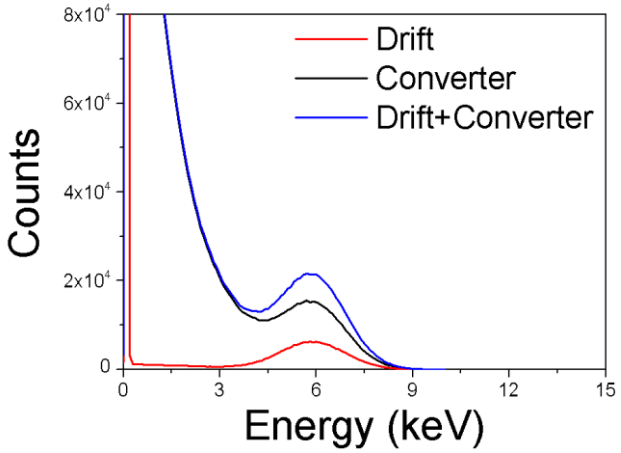


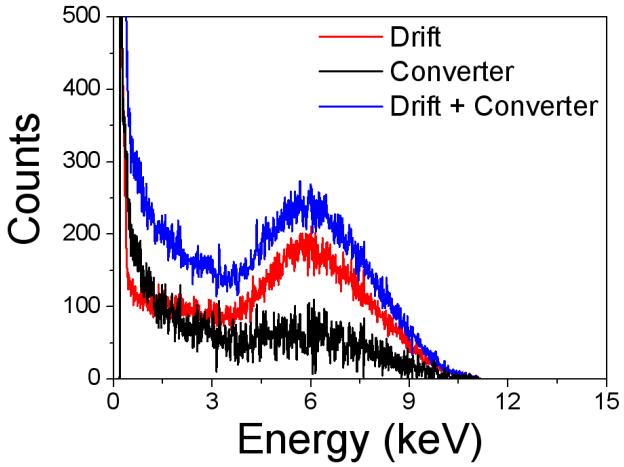


Efficiency ≈ 92%

Small Efficiency loss due to electron diffusion

10 mm height Converter



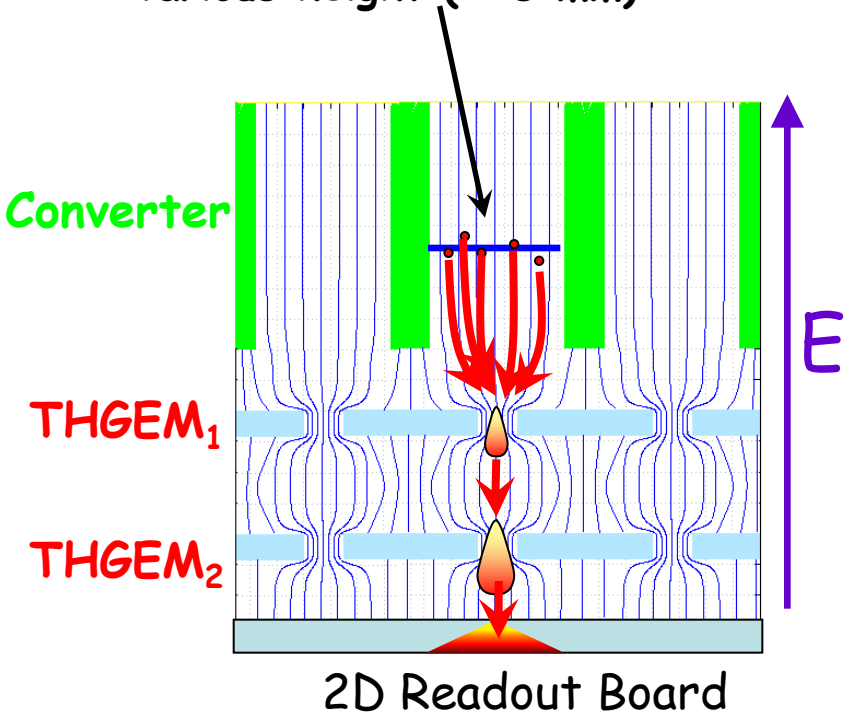


Efficiency ≈ 30%

Significant loss of Efficiency due to charging up of the foils &/or secondary effects (Distorted converter field)

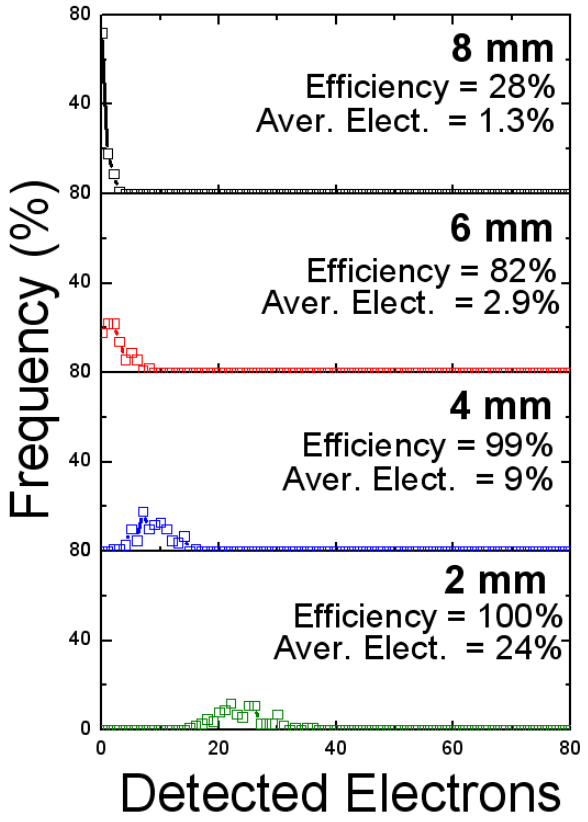
Transport Efficiency (Garfield simulation)

100 electron per event simulated in the gas gap at various height (2-8 mm)



Detected Event ➔ at least one electron focused in the THGEM hole

Charge lost due to electron diffusion!

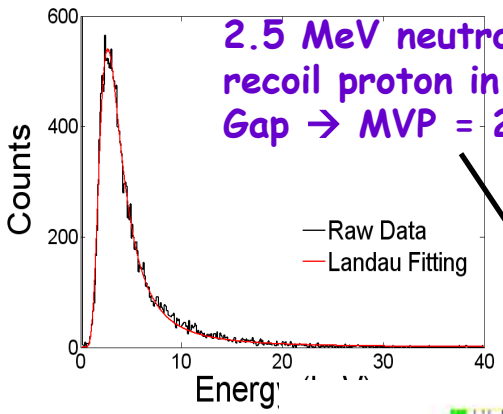


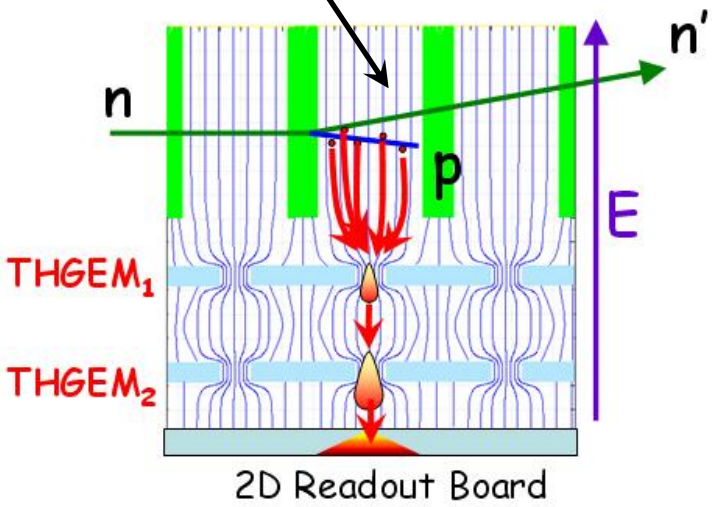
for 6 mm height ➔ Aver. Transport efficiency = 95% (≈ measured efficiency soft X-rays)

for 10 mm height ➔ Aver. Transport efficiency = 70% (> measured efficiency soft X-rays)

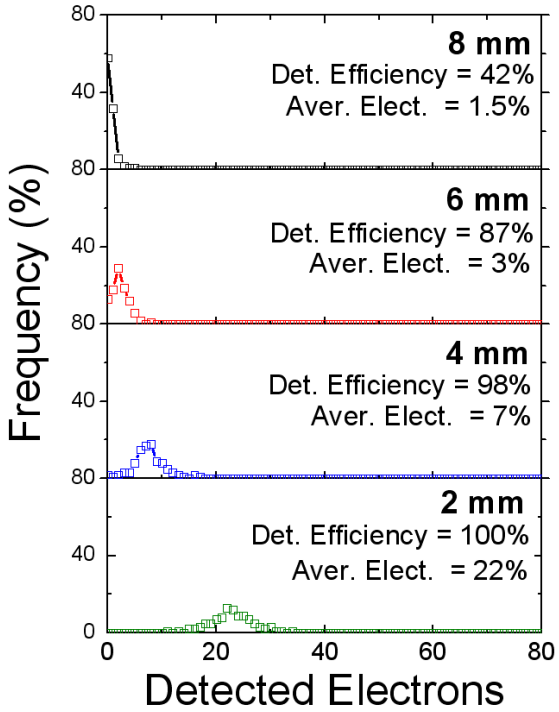
Charging up!

Detection Efficiency (fast neutron)





Detected Event → at least one electron focused in the THGEM hole



6 mm height converter:
Aver. Transport efficiency = 97%

-) Conversions efficiency ≈ 8% for ~300 foils
-) Transport Efficiency ≈ 97% for 6 mm height, 0.6 mm gas gap
-) Discrimination threshold (front-end electronics) ≈ 90%

Estimated Fast-n Detection Efficiency ≈ 7%

Summary & Future Plan

Goal ➔ TWO-FAST:

Fast neutron tomographic ➔ 2D cross-sectional images

Main Application: non-destructive testing for the nuclear energy industry:

multi-phase flow, spent nuclear fuel bundles inspection, safeguards …

Others: detection of SNM, explosive (border control), material science …

Two Detector technologies ➔ Feasibility study

Gaseous Detector (THGEM)

New Idea → many n-to-p converters, single 2D Detector readout

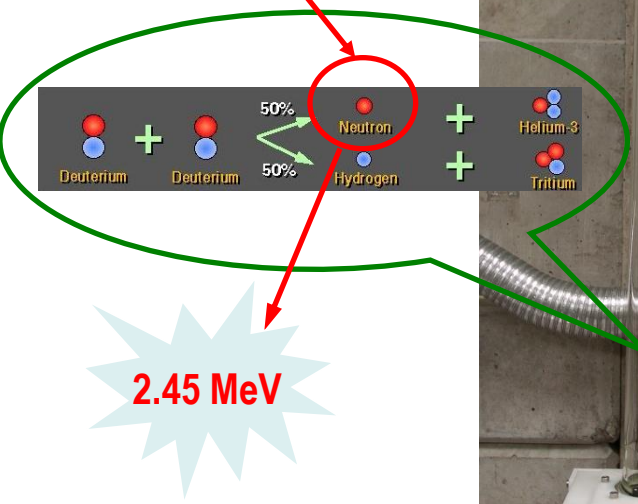
* Expected detection efficiency ~7% (300 foils)
* 1D Radiography, spatial resolution ~ 1 mm
* Low sensitivity to gamma background

* 10x10 cm2 imaging detector prototype ready for neutron
  with antistatic HDPE multi-layers converter produced using 3D printing
  Converter thickness = Gas gap ≈ 0.6 mm (83 layers)
* Improvement of charge-readout electronics
* Implementation with TWO-FAST compact D-D generator

Compact, pulsed neutron generator

1. Emitting spot size:

Ø2mm

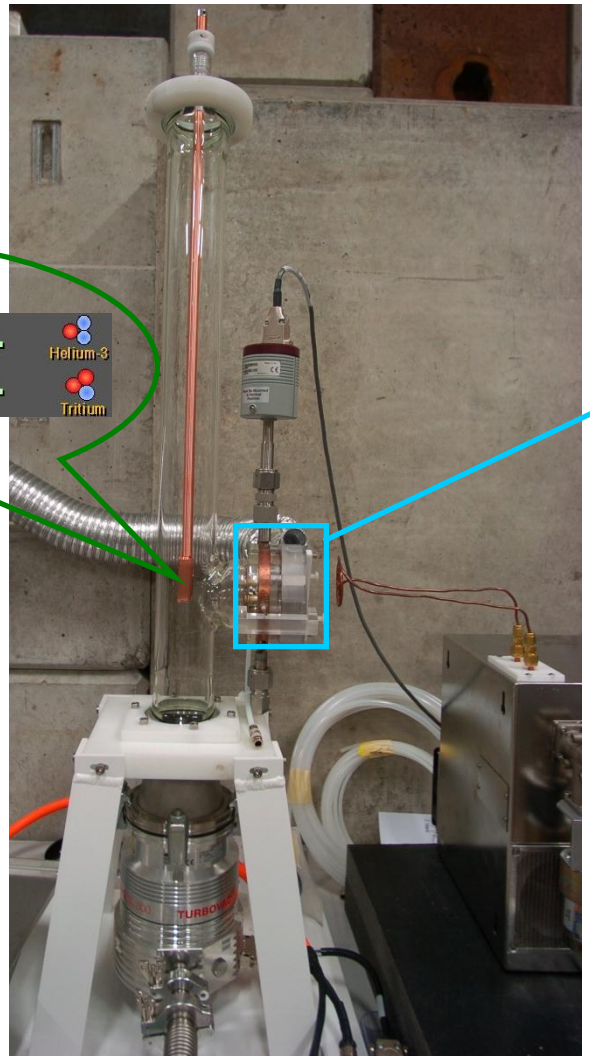


2. Pulsed operation:

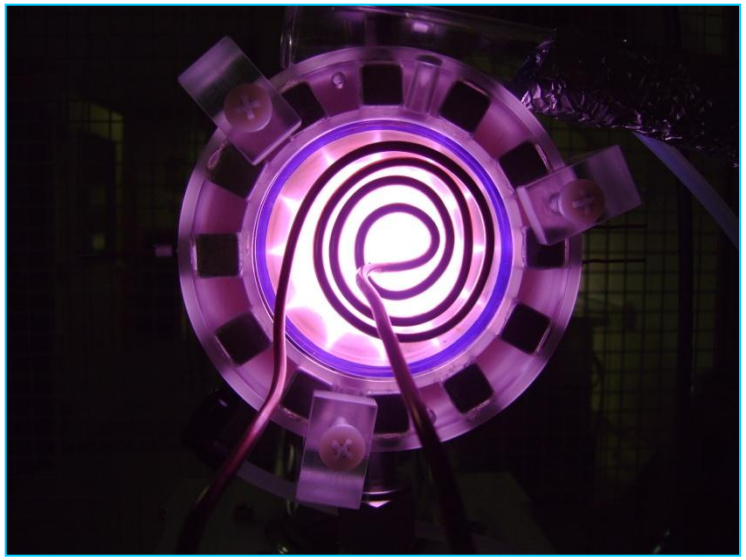
1kHz; D.F.:1-10%

3. Nominal yield:

10^8 neutrons/s



Burning plasma in the RF-driven ion source with external antenna



High fraction (>90%) mono-atomic plasma

Cooperation: Prof. Ka-Ngo Leung, Berkeley