Neutron Detectors

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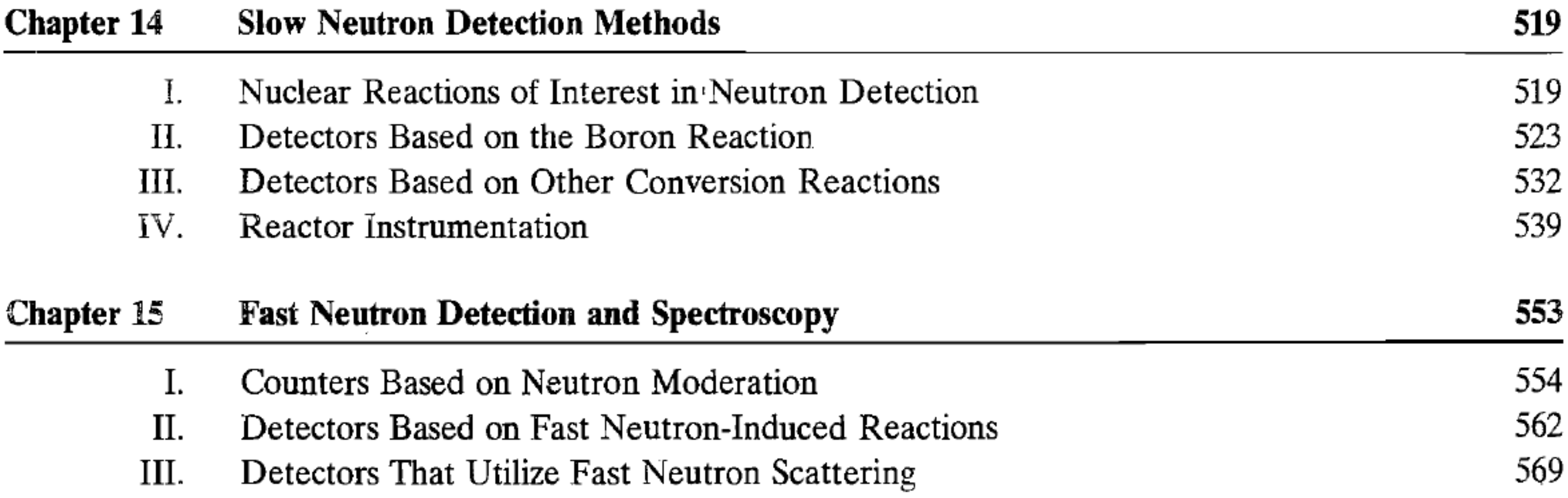
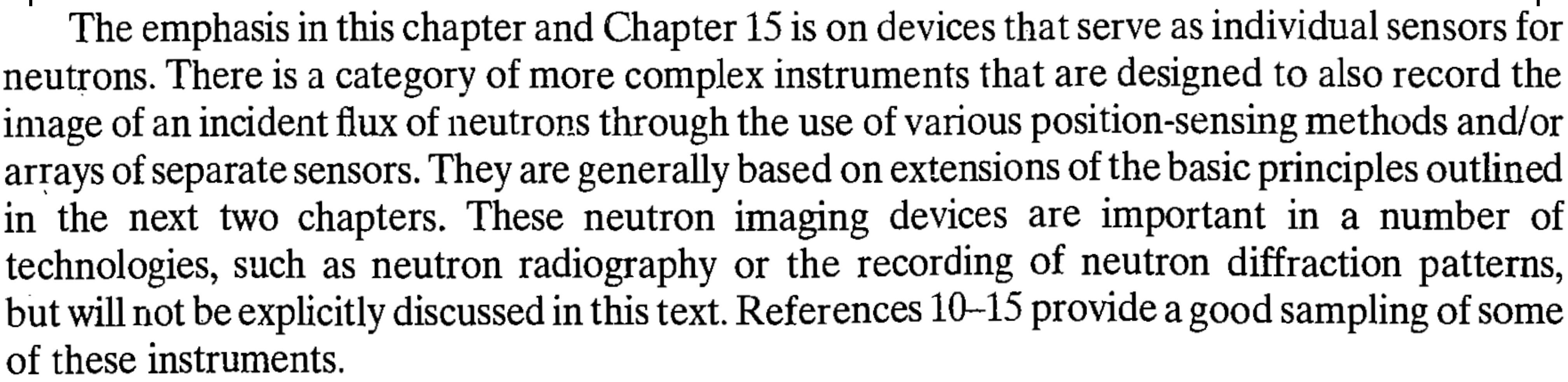
Main reference on radiation detectors:
Glenn F KNOLL, *Radiation Detection and Measurement*



However…



The emphasis in this chapter and Chapter 15 is on devices that serve as individual sensors for neutrons. There is a category of more complex instruments that are designed to also record the image of an incident flux of neutrons through the use of various position-sensing methods and/or arrays of separate sensors. They are generally based on extensions of the basic principles outlined in the next two chapters. These neutron imaging devices are important in a number of technologies, such as neutron radiography or the recording of neutron diffraction patterns, but will not be explicitly discussed in this text. References 10–15 provide a good sampling of some of these instruments.

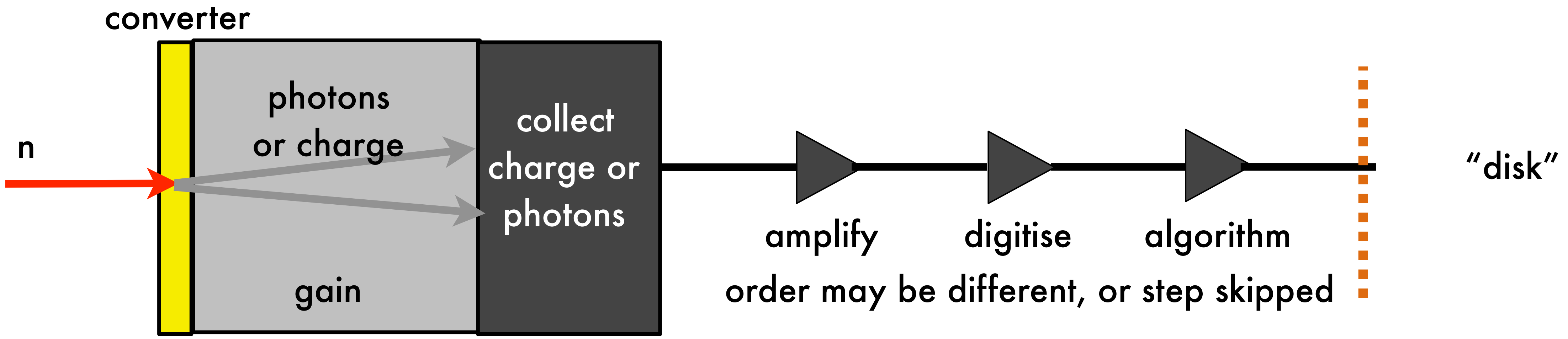
Thermal neutron detectors would deserve a dedicated book!

But you find a good overview chapter in the book
Carpenter, Loong
Elements of Neutron Scattering Techniques and Applications

Neutron Detectors

- How does one “detect” a neutron?
  - Can’t directly detect slow neutrons —they carry too little energy
  - Need to produce some sort of measurable quantitative (countable) electrical signal
- Need to use nuclear reactions to convert neutrons into charged particles (or photons)
- Then one can use some of the many types of charged particle detectors
  - Gas proportional counters and ionization chambers
  - Scintillation detectors
  - Semiconductor detectors

Efficient neutron converters a key component for neutron detectors



converter

n

photons
or charge

gain

collect
charge or
photons

amplify

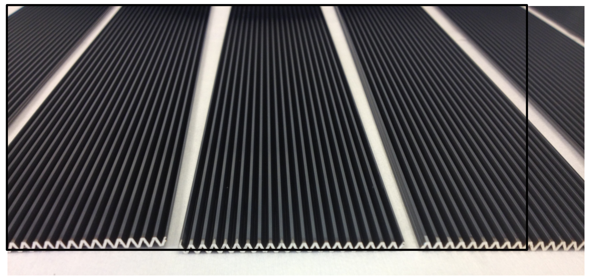
digitise

algorithm

order may be different, or step skipped

“disk”

“Converter” *“Detector”* *“Electronics”*



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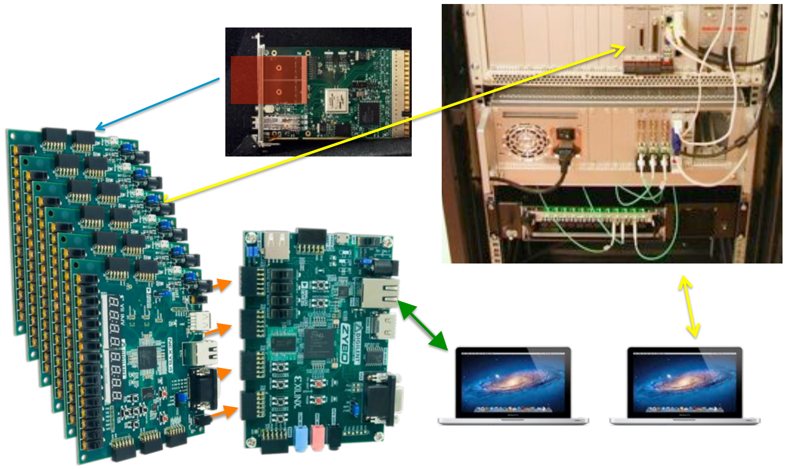
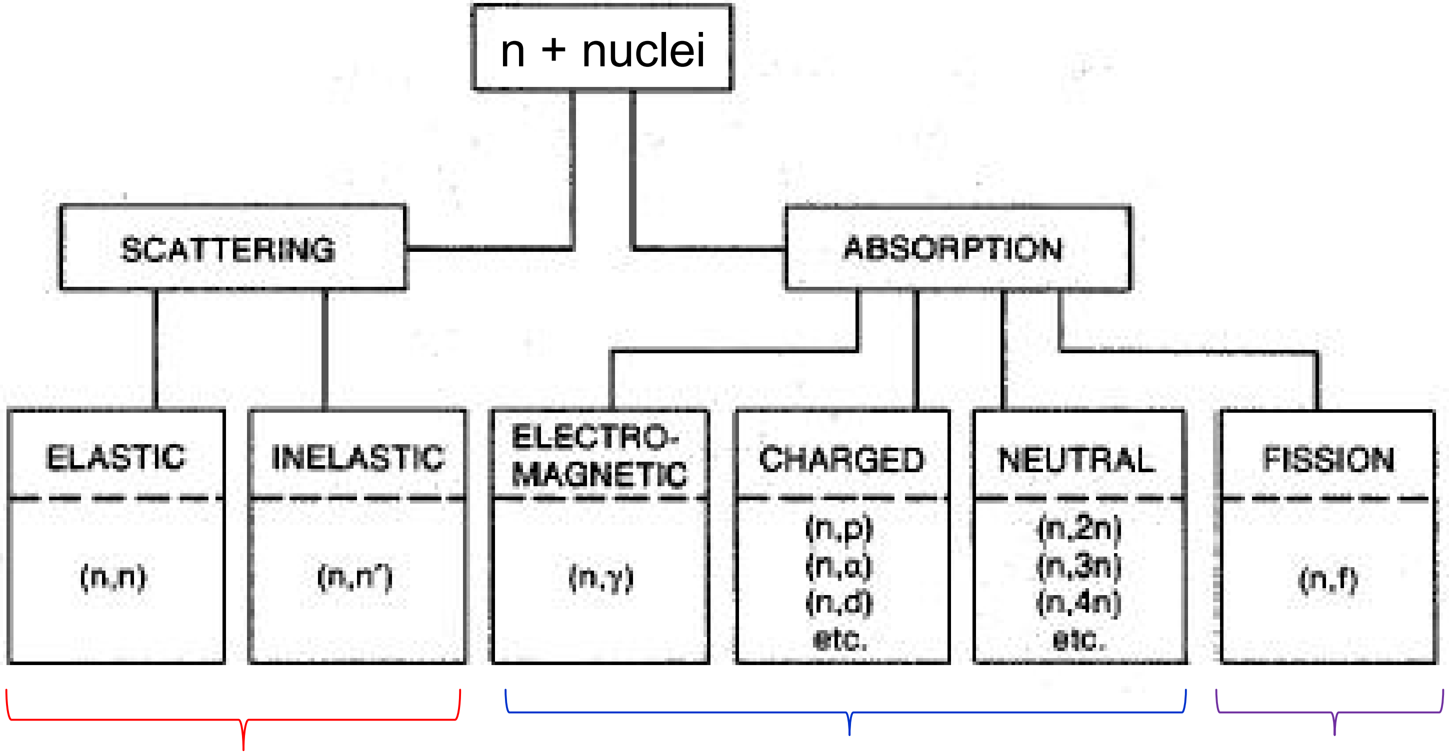


Challenges in neutron detection

- Neutrons have no charge: they do not produce ionizations or excitations in matter directly; neutrons are difficult to stop.
- Background : main component gamma-rays; discrimination against gamma-rays is not easy.
- High detection rates are often required: usually neutron detectors are used in a regions of high neutron (and gamma-ray) flux
- Cross-sections of neutron reactions on which neutron detectors can be based decrease with increasing neutron energy ⇒ fast neutrons with high efficiency is particulary difficult

Interaction of neutrons with matter

- No electric charge → no electromagnetic interaction (or too weak)
- Only strong interaction with the nuclei



n + nuclei

SCATTERING

ABSORPTION

ELASTIC (n,n)

INELASTIC (n,n')

ELECTRO-MAGNETIC (n,γ)

CHARGED (n,p) (n,α) (n,d) etc.

NEUTRAL (n,2n) (n,3n) (n,4n) etc.

FISSION (n,f)

used for **fast** neutrondetection

used for **slow** neutron detection

fast and slow neutrondetection

Slow Neutron Detection

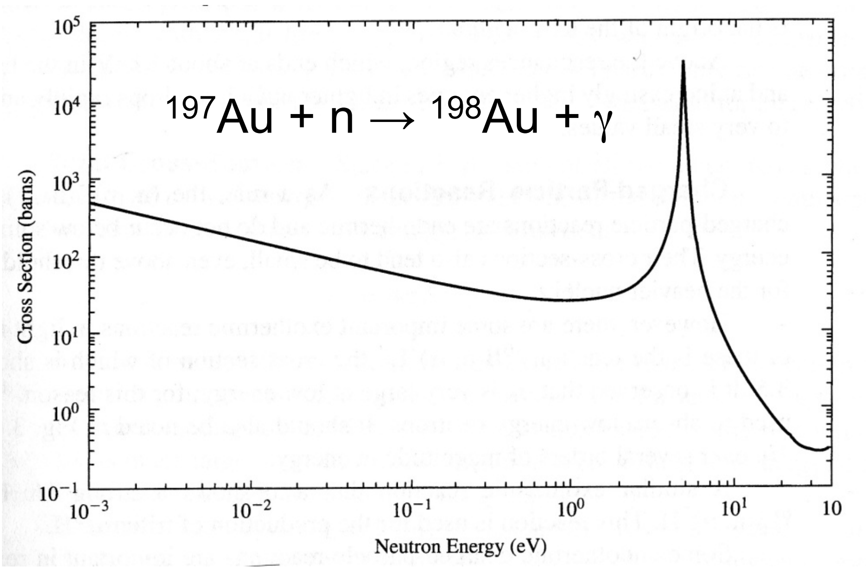
- Cross-section for elastic (potential) scattering : $\sigma_e = 4\pi R^2$
- Cross-section for capture reaction follows characteristic 1/v dependence for low neutron energies
- The form can be derived from Breit-Wigner resonance lineshape (single level resonance formula), e.g. neutron capture and capture-independent gamma-ray emission (radiative capture):

$$\sigma_{capture} = \pi \bar{\lambda}^2 \frac{\Gamma_n \Gamma_\gamma}{\left(E - E_R\right)^2 + \left(\Gamma/2\right)^2}$$

$E << E_R; \Gamma_n \approx v; \bar{\lambda} = \hbar/mv : E_R$ Resonance energy

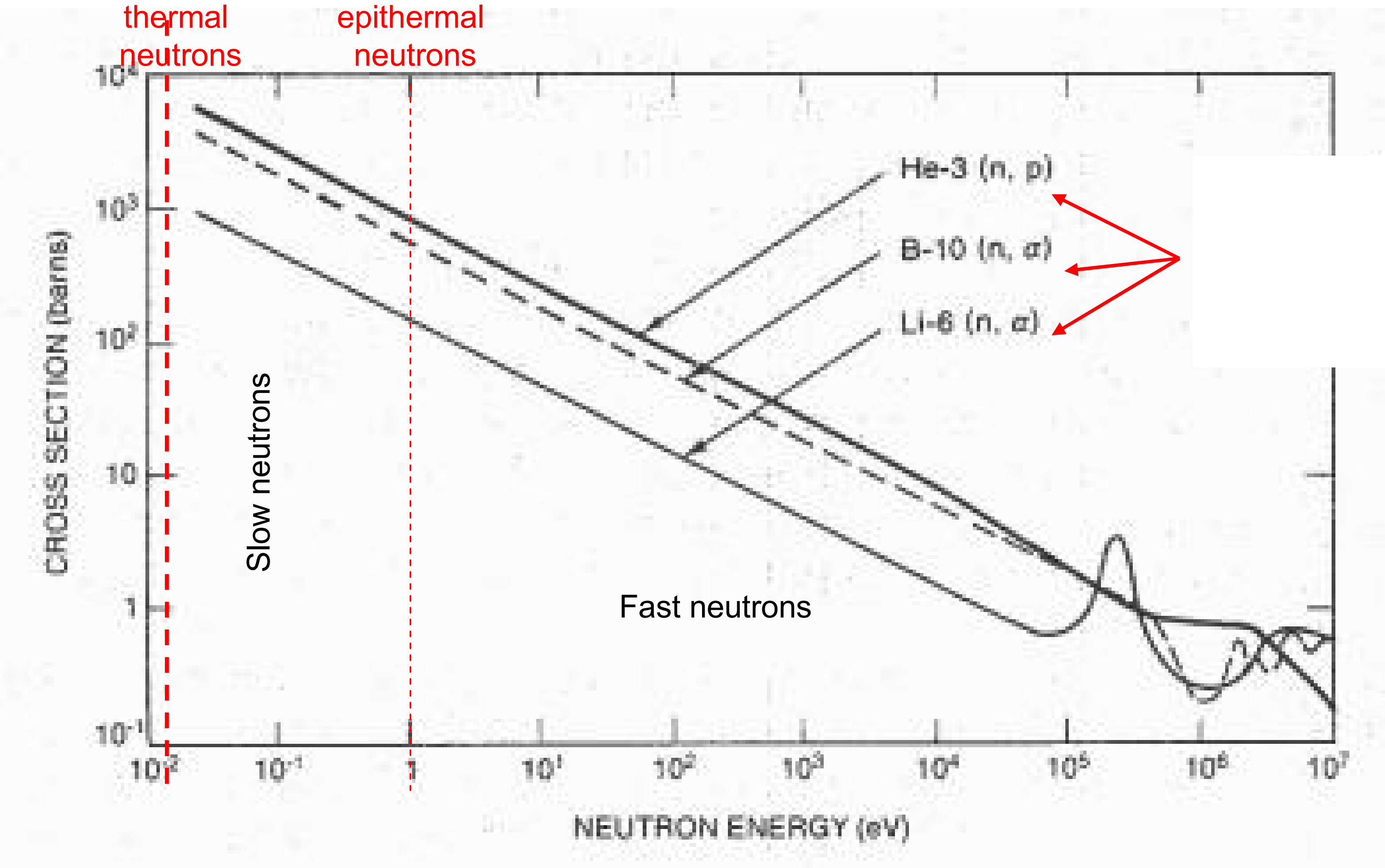
Primary decay is γ emission and independent of neutron $\Rightarrow \Gamma \approx \Gamma_\gamma$

$$\Rightarrow \quad \sigma \propto \frac{1}{v}$$



Commonly Used Neutron Reactions

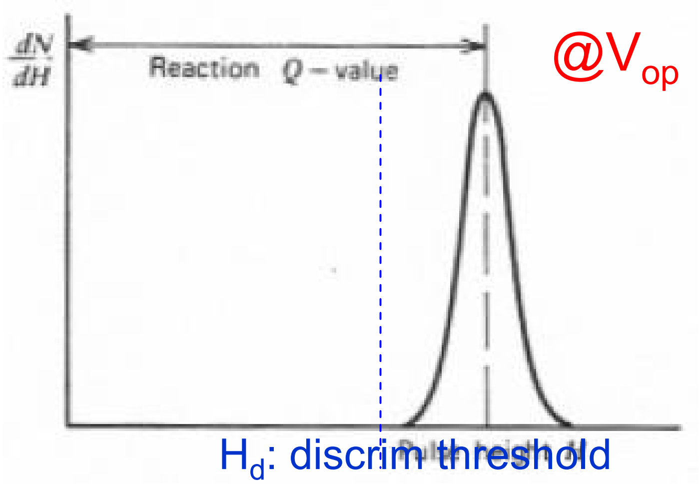
$n + {}^{3}\mathrm{He} \rightarrow ({}^{4}\mathrm{He})^{*} \rightarrow p + {}^{3}\mathrm{H}$, $Q = 0.765$ MeV, target abundance ~ $1.4\mathrm{x}10^{-4}$ % (5.3 kb)	(n,p)
$n + {}^{6}\mathrm{Li} \rightarrow ({}^{7}\mathrm{Li})^{*} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{H}$, $Q = 4.78$ MeV, target abundance ~ 7.5% (940 b)	(n,α)
$n + {}^{10}\mathrm{B} \rightarrow ({}^{11}\mathrm{B})^{*} \rightarrow {}^{7}\mathrm{Li}^{*} + {}^{4}\mathrm{He}$, $Q = 2.31$ MeV, 94% branch, nat. abund. ~20 % (3.8kb) $\rightarrow {}^{7}\mathrm{Li} + {}^{4}\mathrm{He}$, $Q = 2.79$ MeV, 6% branch	(n,α)
$n + {}^{113}\mathrm{Cd} \rightarrow ({}^{114}\mathrm{Cd})^{*} \rightarrow {}^{114}\mathrm{Cd} + \gamma$, $Q \sim 8$ MeV, target abundance ~ 12% (21 kb)	(n,γ)
$n + {}^{157}\mathrm{Gd} \rightarrow ({}^{158}\mathrm{Gd})^{*} \rightarrow {}^{158}\mathrm{Gd} + \gamma$, $Q \sim 8$ MeV, target abundance ~ 16% (255 kb)	
$n + {}^{235}\mathrm{U} \rightarrow ({}^{236}\mathrm{U})^{*} \rightarrow$ (fission fragments), $Q \sim 200$ MeV, target abundance ~ 0.7%	(n,f)

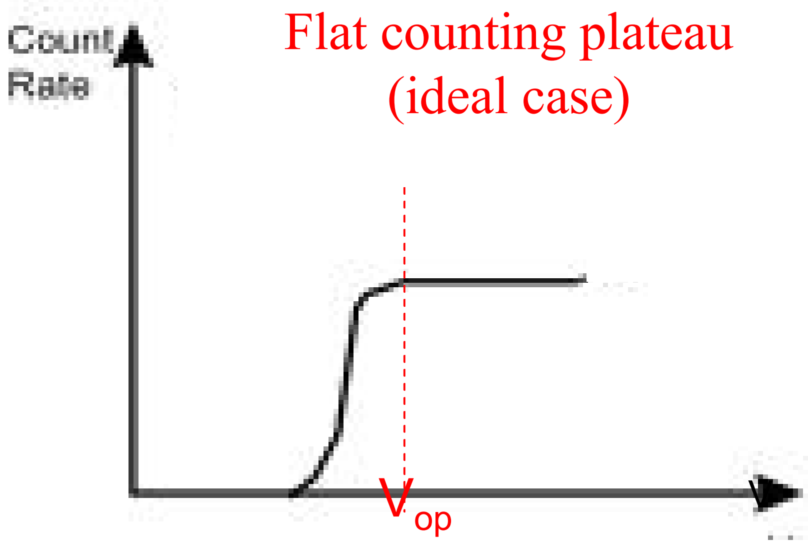


Cross section vs neutron energy for some reactions of interest in neutron detection (G. Knoll)

Principles of neutron detection: reaction-based detectors

Ideally, for a reaction-based detector
and for **$E_n << Q$:**





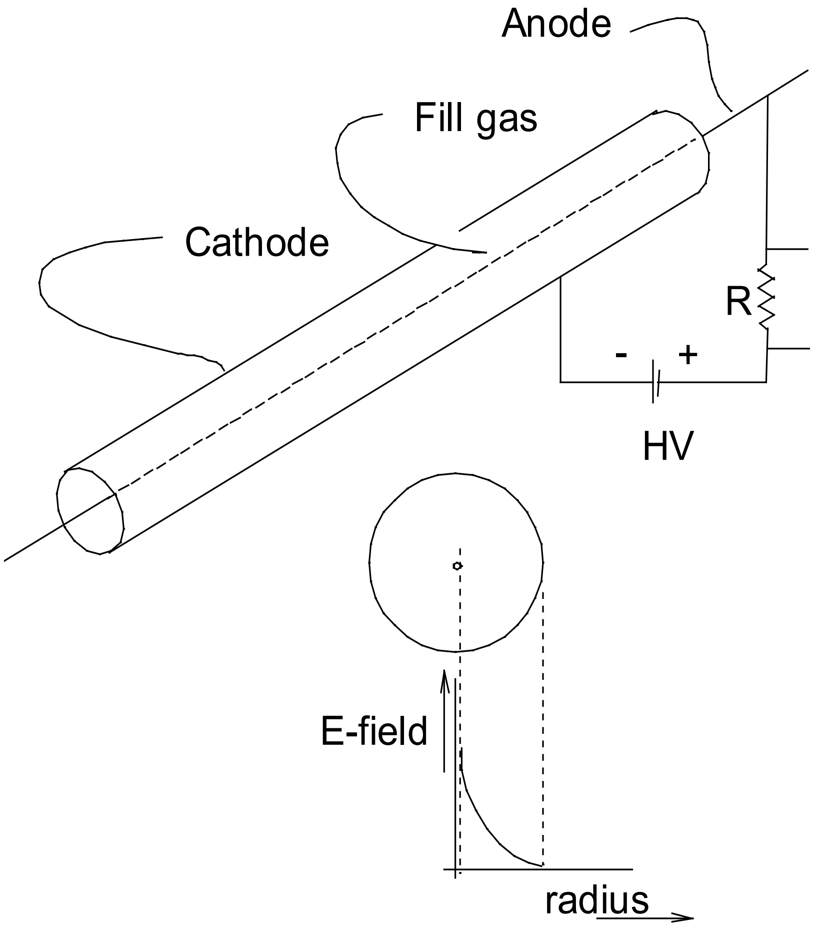
NOTE : **spectrum does not give any information on the energy of the incident neutron**

Large Q → better discrimination between neutrons and gammas (pulses due to γs not represented)

Flat plateau allows stable counting operation

Gas Detectors

Gas Proportional Counter



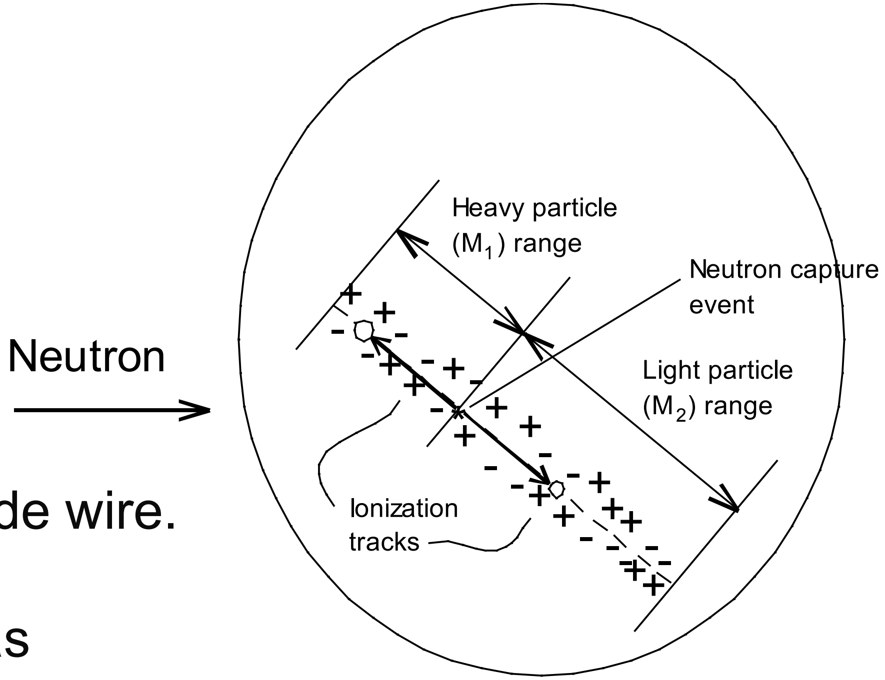
$$n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 0.76\ MeV$$

$$\sigma = 5333\ \frac{\lambda}{1.8}\ \text{barns}$$

~25,000 ions and electrons (~4×10^{-15} coulomb) produced per neutron

Gas Detectors

Ionization tracks in
proportional counter gas



Electrons drift toward the central anode wire. When they get close, they accelerate sufficiently between collisions with gas atoms to ionize the next atom. A *Townsend avalanche* occurs in which the number of electrons (and ions) increases the number many-fold, about x10^3. Separation of these charges puts a charge on the detector, which is a low-capacitance capacitor, causing a pulse in the voltage that can be amplified and registered electronically.

The ^{3}He Proportional Counter

- n + ^{3}He → p + ^{3}H, Q = 764 keV (^{3}H = triton (t))
- Assume $E_n \ll Q$; $Q = E_p + E_t$; Momentum conservation:

$$m_p v_p = m_t v_t$$

$$\Rightarrow \sqrt{2E_p m_p} = \sqrt{2E_t m_t}$$

$$\Rightarrow E_p = \frac{m_t}{m_p} E_t = \frac{m_t}{m_p}(Q - E_p)$$

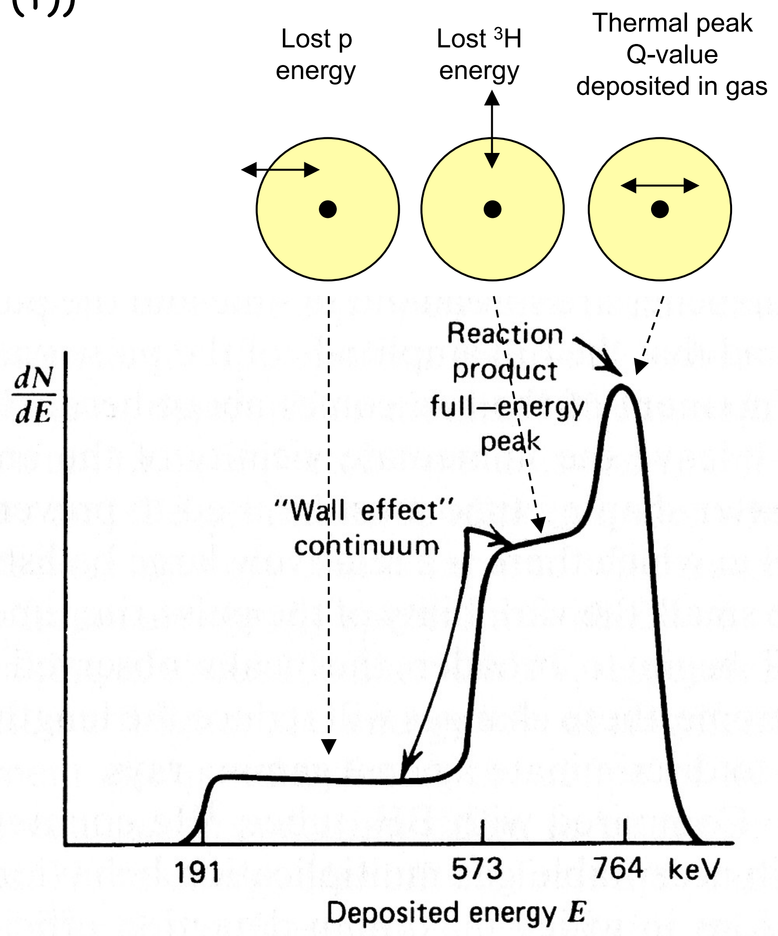
$$\Rightarrow E_p = \frac{m_t}{m_p + m_t} Q$$

⇨ E_p = 573 keV; E_t = 191 keV

⇨ Range R in Si: R_p ~ 6μm, R_t ~ 5μm

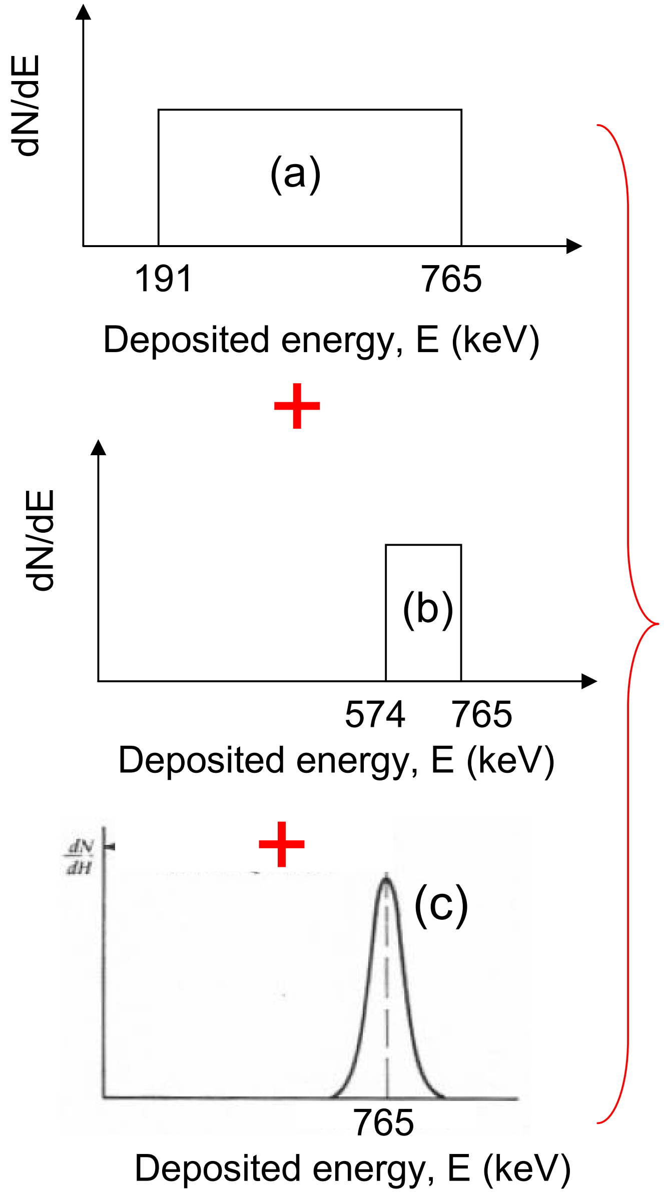
⇨ Ranges in gas ~1000 x range in solid ~ few mm's (Rρ ~ 0.25 mg/cm^2 for α in He gas)

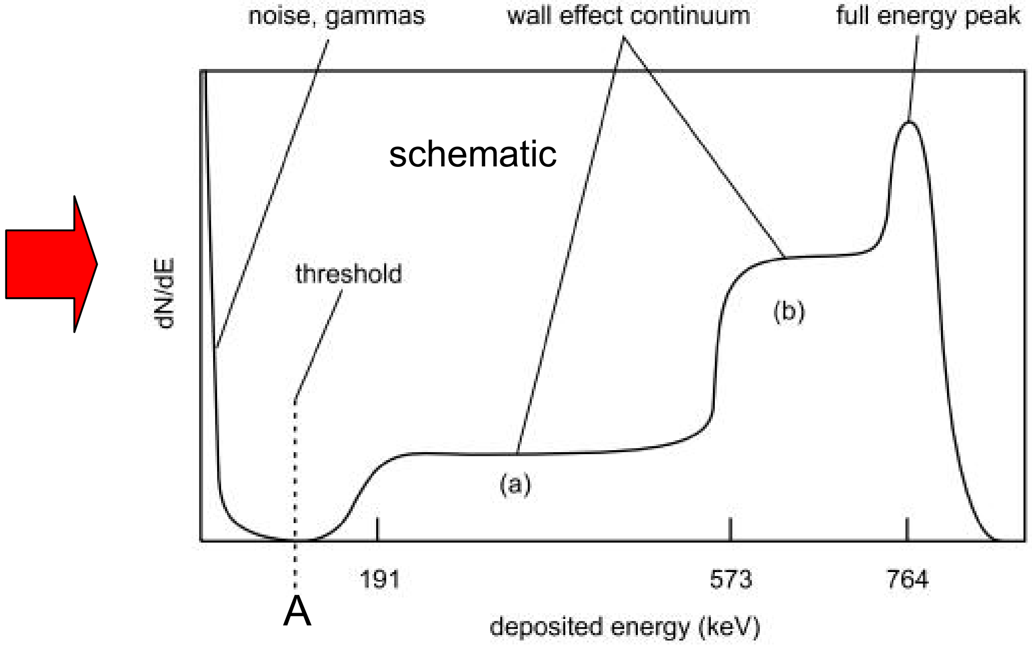
The wall effect



Wall effect depends on tube dimensions and gas pressure

^{3}He counters: n/γ discrimination





- Spectrum depends on size and geometry detector
- γ interactions produce small amplitude pulses that can be eliminated by amplitude discrimination
- For counting purposes, the threshold should be set around A

Sizes of Proportional Counters

- PCs come in many sizes.
  - Diameters from ~ 5. mm to 50 mm.
  - Fill gas pressures are highest for small diameters,
    up to 40 atm, and lowest for large diameters 2.~ 3. atm.
  - Lengths vary from cm to meters; the longer detectors,
    up to about 3. m long, are typically those of
    larger diameter.

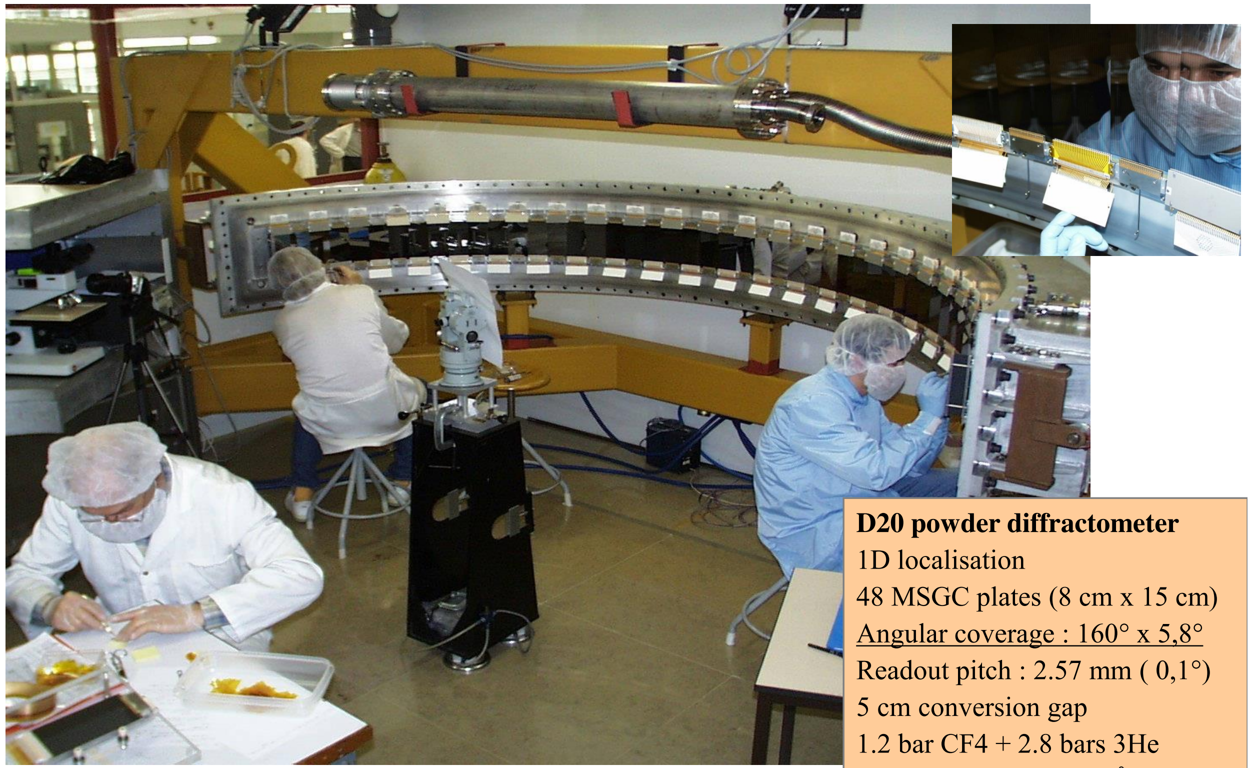
MAPS Detector Bank (at ISIS)

3He based detectors

- Helium-3 Tubes most common
- Typically 3-20 bar Helium-3
- 8mm-50mm diameter common
- Using a resistive wire, position resolution along the wire of ca. 1% possible

can be large arrays of 10s of m^2

Curved 1D MSGC for the D20 Powder Diffractometer (2000)



D20 powder diffractometer
1D localisation
48 MSGC plates (8 cm x 15 cm)
Angular coverage : 160° x 5,8°
Readout pitch : 2.57 mm (0,1°)
5 cm conversion gap
1.2 bar CF4 + 2.8 bars 3He
Efficiency 60% @ 0.8 Å

- First micro pattern gaseous detectors was MSGC invented by A Oed at the ILL in 1988
- Rate and resolution advantages
- Helium-3 MSGCs in operation

Detection efficiency

$$\varepsilon = 1 - \exp(-N\sigma d)$$

Approximate expression for low efficiency:

$$\varepsilon = N\sigma d$$

Here:

σ = *absorption cross section (energy dependent)*
N= *number density of absorber*
d= *thickness*

$N = 2.7\text{x}\ 10^{19}\ \text{cm}^{-3}$ *per atm for a gas at 300 K.*
For 1-cm thick ^{3}*He at 1 atm and "thermal" neutrons,*
$\varepsilon = 0.13$.

The BF_3 slow neutron detector

$n + {}^{10}B \rightarrow ({}^{11}B)^*$

$\rightarrow {}^{7}Li^* + {}^{4}He$, Q = 2.31 MeV [94%]

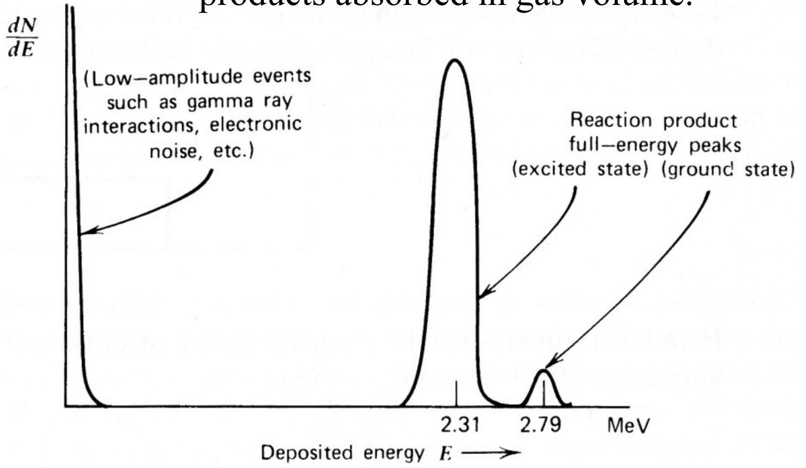
K.E. 0.84 MeV + 1.47 MeV

$\rightarrow {}^{7}Li + {}^{4}He$, Q = 2.79 MeV [6%]

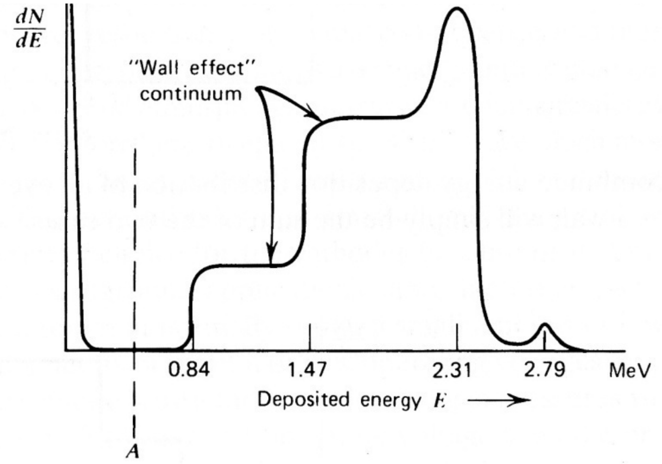
- BF_3 gas, enriched to >90% of ${}^{10}B$
- Operated as proportional or G-M counter
- However, recombination and formation of negative ions require lower pressure P < 1atm
  - Range of α-particles ~ 10 mm
  - Pronounced wall effect
- As in ${}^{3}He$ tube, spectrum reflects response of detector, NOT neutron energy

BF_3 counters:
P ~ 0.5 – 1 atm
2000 – 3000 V
M ~ 100-500

“Ideal” response: large tube, all reaction products absorbed in gas volume.



Obs. response due to partial energy loss in tube walls



BF_3 proportional counters

$^{10}B(n,\alpha)$ reaction is employed in BF_3 proportional tubes where BF_3 gas is the neutron converter and the detector medium simultaneously.

•The BF_3 gas is enriched in ^{10}B (up to more than 90%) to increase the sensitivity to neutrons (natural B has ~20% ^{10}B)

•The range of 2.31 MeV alpha-particle @ 1 atm: ~1 cm

wall effect: not all energy deposited in gas

BF_3 counters: properties

- Wall effect are reduced by making the detector larger or rising BF_3 pressure

- Small tubes are acceptable as long as a clear counting plateau is maintained.

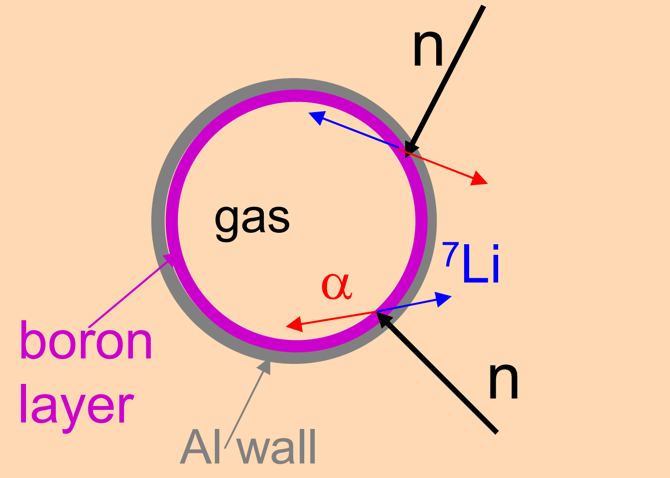
- Detection efficiency decreases as neutron energy increases (1/v behavior of cross section)

- Aging (degradation of performance after ~10^{10}-10^{11} counts)

- At high flux, multiple γ pulses in short time succession may give a net pulse large enough to be mistaken for a neutron pulse

Boron-lined detectors

- Boron deposited on the inner surfaces of the chamber is the target material for conversion of the neutrons into a ^{7}Li and an α ($^{10}B(n,\alpha)^7Li$);
- ^{7}Li or α (not both) enter the chamber.
- As ^{7}Li or α are charged, they are detected in the gas filling the detector



Schematic ilustrating the operation principle of a boron-lined detector

- α-range in boron is ~1mg/cm^2 ⇒ boron plating should be thin ⇒ the neutron detection efficiency (~10%) is lower in ^{3}He or BF_3 counters.

Boron-lined Proportional Counters

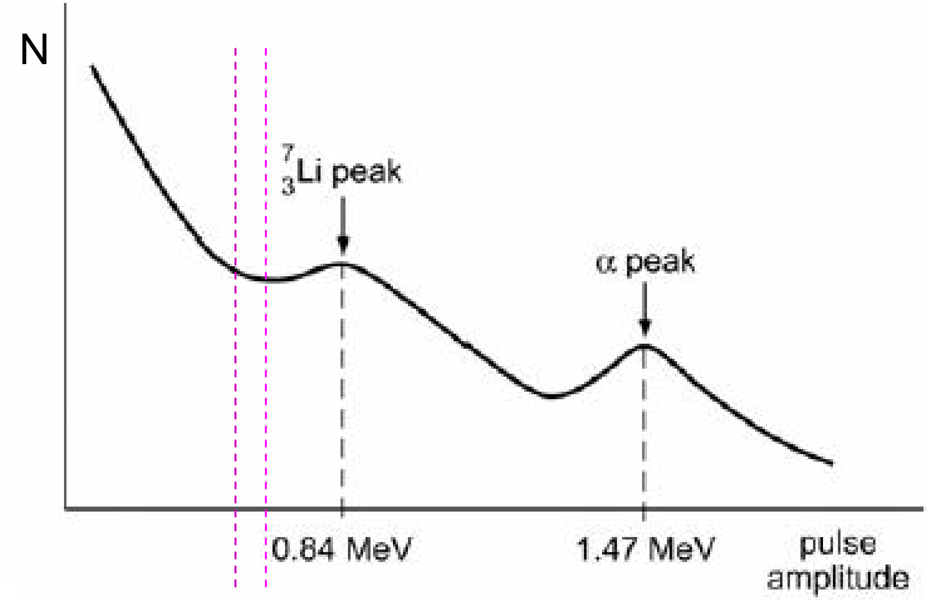
- interior walls of a conventional proportional counter coated with solid boron.

- use standard proportional gas

- Neutron interactions with ^{10}B take place in the wall of the counter→ Only one of the two emitted particles (^{7}Li or α) reaches the gas with some fraction of its initial energy

the energy of particles entering the gas and producing pulses varies:

^{7}Li: from 0 to 0.84 MeV
α: from 0 to 1.47 MeV



threshold ~ here

As there is no well-defined “valley” to set the threshold in, the count rate plateau curve is ~10%/100V

Comparing Boron-lined with BF3 proportional counters:

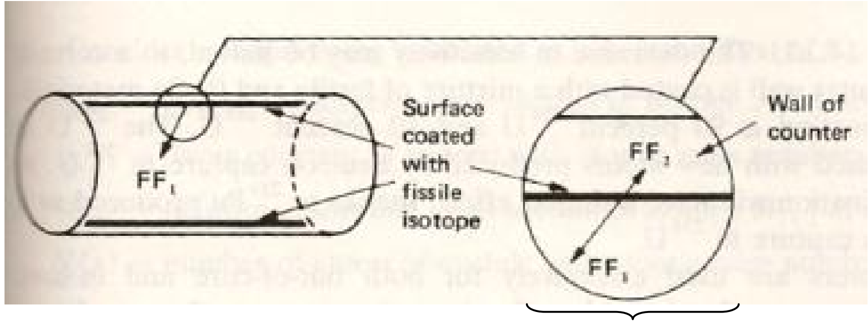
- A more suitable proportional gas can be used
- Higher gamma-ray insensitivity (due to lower fill pressure and lower operating pressure)
- Less aging effects
- Can give faster signals (by proper choice of gas)

- worse long-term counting stability
- lower efficiency (~10%)

Fission chambers: principle of operation

Neutron cause fission of the material covering one (or both electrode) of the chamber

The high energy ionising products → output pulses of the ionization chamber.



for slow neutrons, the two FF are emitted in oposite directions

Fission fragments (FF) are very energetic (for example ^{235}U : Q~200 MeV → FF share about 160 MeV);

α and γ background also present;

^{235}U is the most used material; ^{238}U and ^{232}Th are used for fast neutrons

Other fissionable isotopes are ^{239}Pu, ^{237}Np, ^{234}U and ^{233}U.

- The most common filling gas is Argon plus 10% methane (or 2% N_2), with filling pressures typically from 1 to 5 atm (pressure depending on the application). At this pressure the range of FF is ~ a few cm.

Fission chambers

Coating thickness should be as large as possible to increase efficiency

BUT

smaller than the range of fission fragments in the coating material (average range of FF from ^{235}U is ~7 μm ≡13mg/cm^2 coating;

- ➡ Typical coating thickness: 0.02 to 2 mg/cm^2
- ➡ Typical efficiency for thermal neutrons: 0.5 -1% (and even lower for fast neutrons)

Gamma-sensitivity and **neutron efficiency** of some neutron detectors

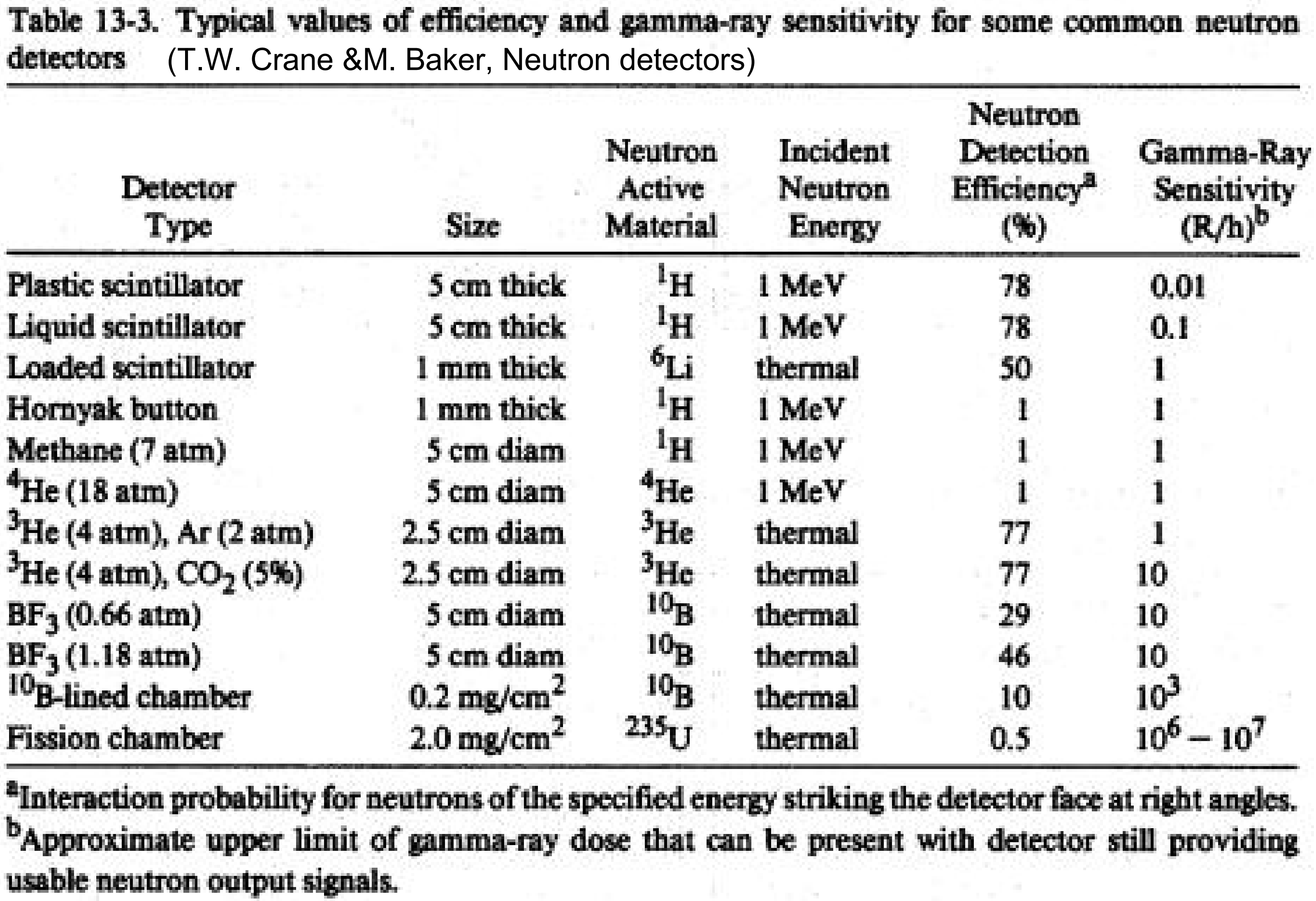


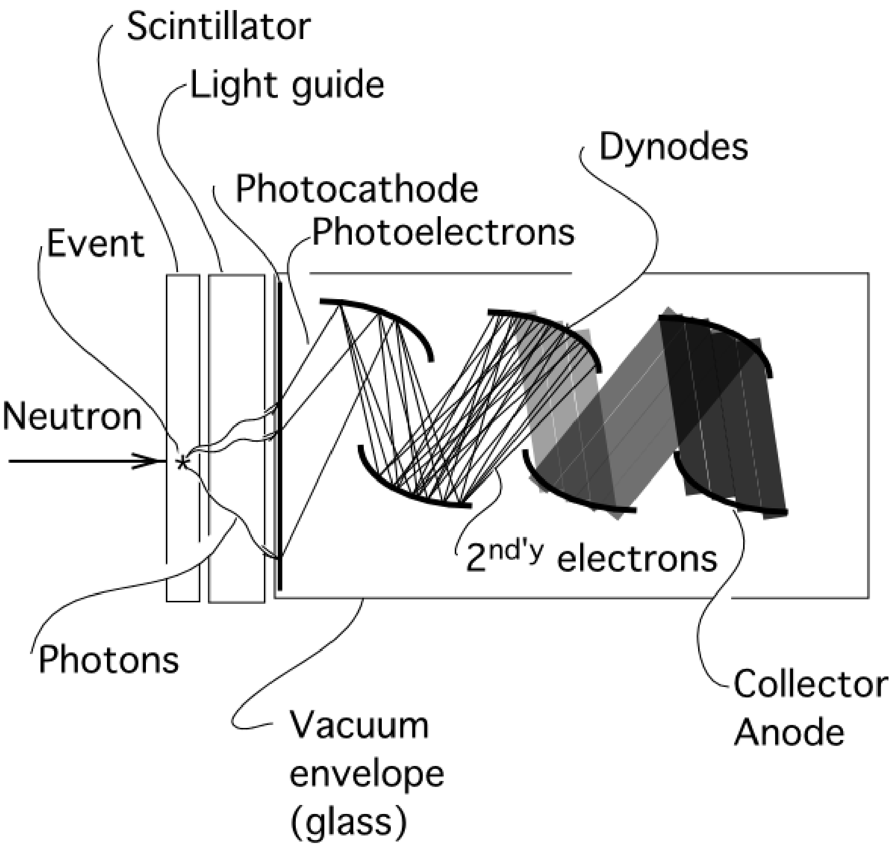
Table 13-3. Typical values of efficiency and gamma-ray sensitivity for some common neutron detectors (T.W. Crane &M. Baker, Neutron detectors)

Detector Type	Size	Neutron Active Material	Incident Neutron Energy	Neutron Detection Efficiency[a] (%)	Gamma-Ray Sensitivity (R/h)[b]
Plastic scintillator	5 cm thick	^1H	1 MeV	78	0.01
Liquid scintillator	5 cm thick	^1H	1 MeV	78	0.1
Loaded scintillator	1 mm thick	^6Li	thermal	50	1
Hornyak button	1 mm thick	^1H	1 MeV	1	1
Methane (7 atm)	5 cm diam	^1H	1 MeV	1	1
^4He (18 atm)	5 cm diam	^4He	1 MeV	1	1
^3He (4 atm), Ar (2 atm)	2.5 cm diam	^3He	thermal	77	1
^3He (4 atm), CO_2 (5%)	2.5 cm diam	^3He	thermal	77	10
BF_3 (0.66 atm)	5 cm diam	^{10}B	thermal	29	10
BF_3 (1.18 atm)	5 cm diam	^{10}B	thermal	46	10
^{10}B-lined chamber	0.2 mg/cm^2	^{10}B	thermal	10	10^3
Fission chamber	2.0 mg/cm^2	^{235}U	thermal	0.5	$10^6 - 10^7$

[a] Interaction probability for neutrons of the specified energy striking the detector face at right angles.

[b] Approximate upper limit of gamma-ray dose that can be present with detector still providing usable neutron output signals.

Scintillation Detectors



$$n + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{H} + 4.79\ \mathrm{MeV}$$

$$\sigma = 940\frac{\lambda}{1.8}\,\mathrm{barns}$$

Some Common Scintillators for Neutron Detectors

Intrinsic scintillators contain small concentrations of ions (“wave shifters”) that shift the wavelength of the originally emitted light to the longer wavelength region easily sensed by photomultipliers.

ZnS(Ag) is the brightest scintillator known, an intrinsic scintillator that is mixed heterogeneously with converter material, usually Li^6F in the “Stedman” recipe, to form scintillating composites. These are only semitransparent. But it is somewhat slow, decaying with ~ 10 μsec halftime.

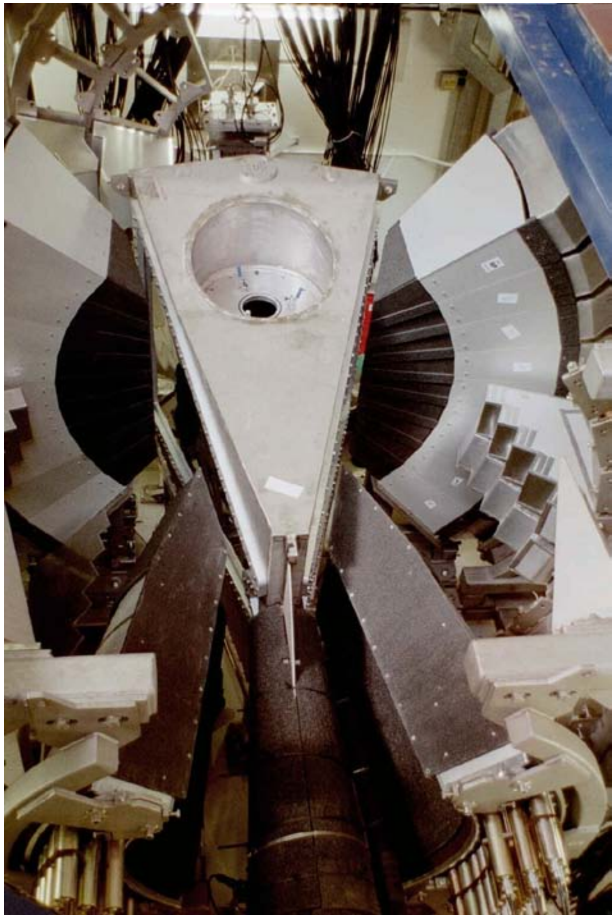
GS-20 (glass,Ce^{3+}) is mixed with a high concentration of Li_2O in the melt to form a material transparent to light.

$Li_6Gd(BO_3)_3$ (Ce^{3+}) (including ^{158}Gd and ^{160}Gd, ^6Li ,and ^{11}B), and $^6LiF(Eu)$ are intrinsic scintillators that contain high proportions of converter material and are typically transparent.

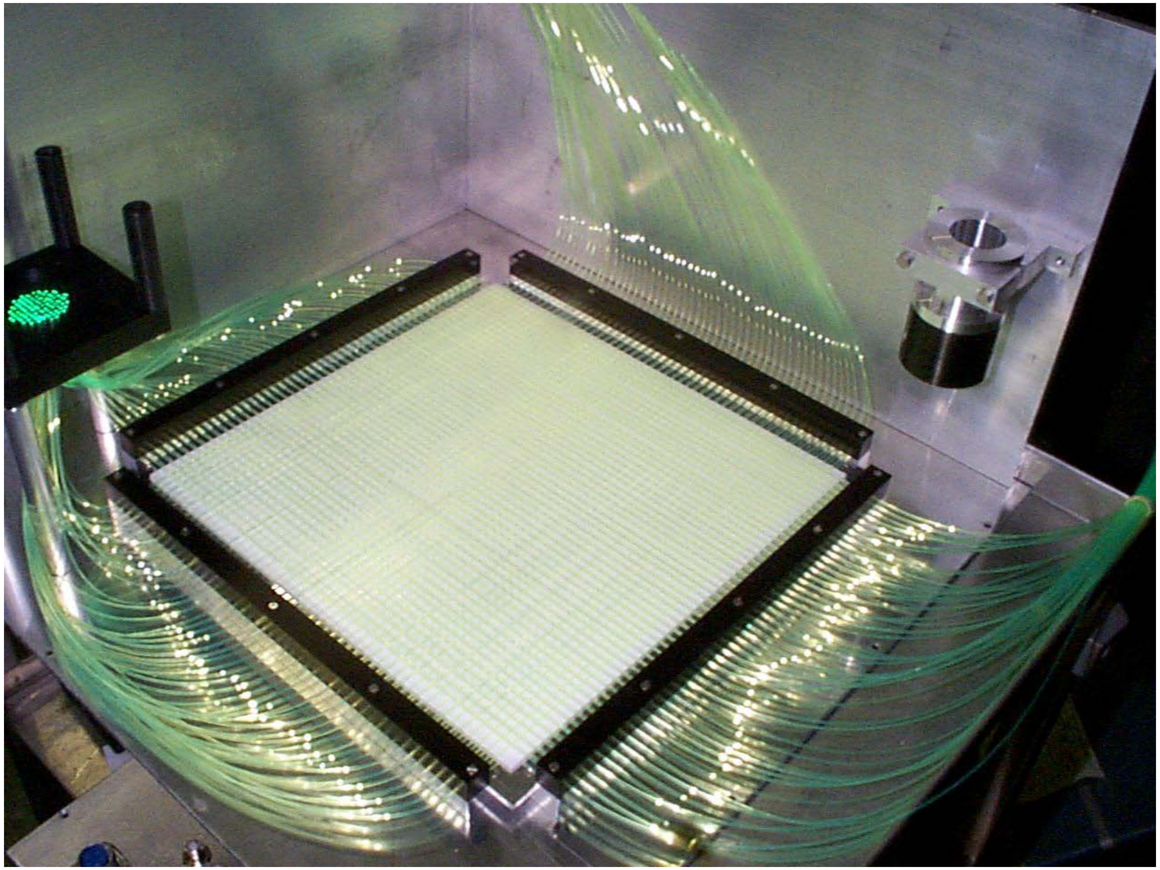
Some Common Scintillators for Neutron Detectors-cont'd

Material	Density of ^{6}Li atoms (cm^{-3})	Scintillation efficiency	Photon wavelength (nm)	Photons per neutron
Li glass (Ce)	1.75×10^{22}	0.45 %	395 nm	~7,000
LiI (Eu)	1.83×10^{22}	2.8 %	470	~51,000
ZnS (Ag) - LiF	1.18×10^{22}	9.2 %	450	~160,000
$Li_6Gd(BO_3)_3$ (Ce),	3.3×10^{22}		~ 400	~40,000
YAP	NA		350	~18,000 per MeV gamma

GEM Detector Module



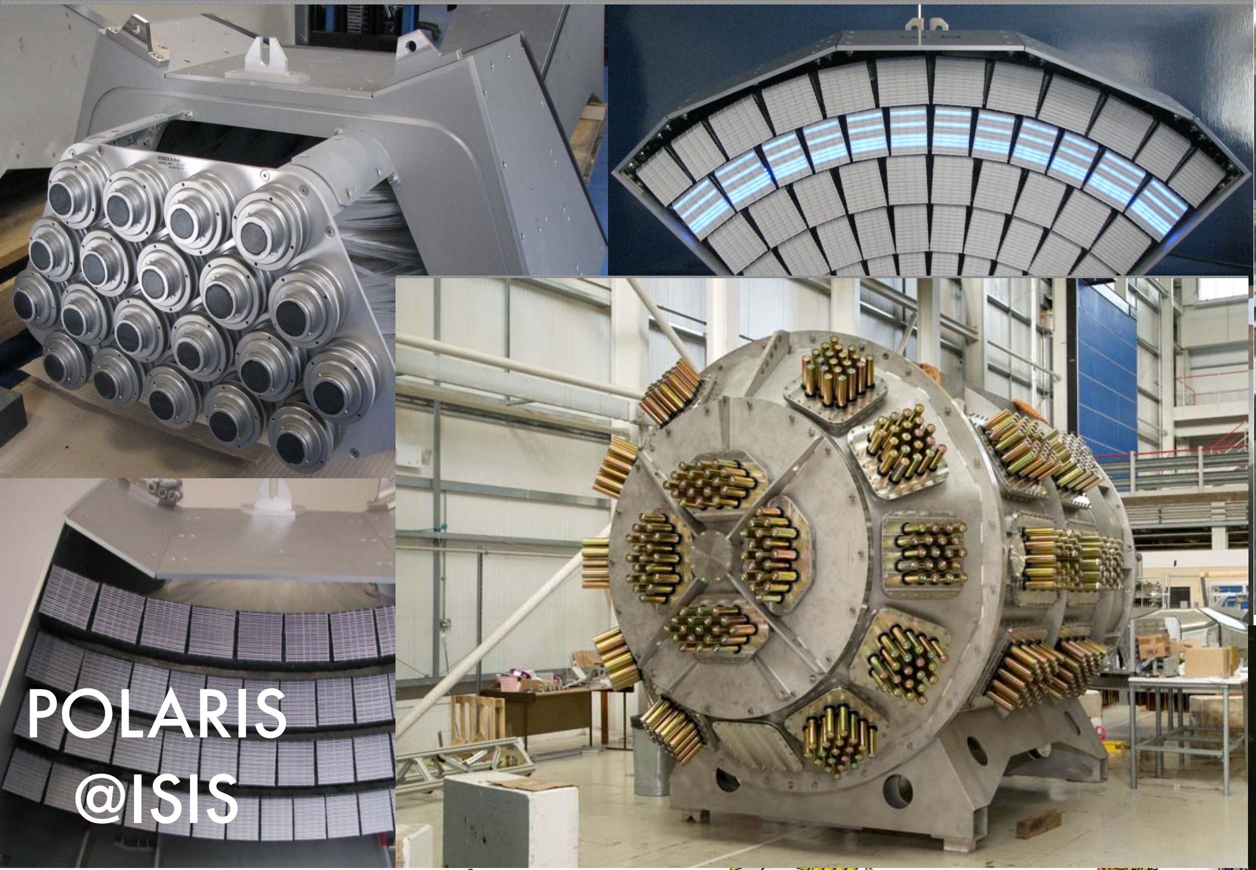
SNS 2-D Scintillation Detector Module



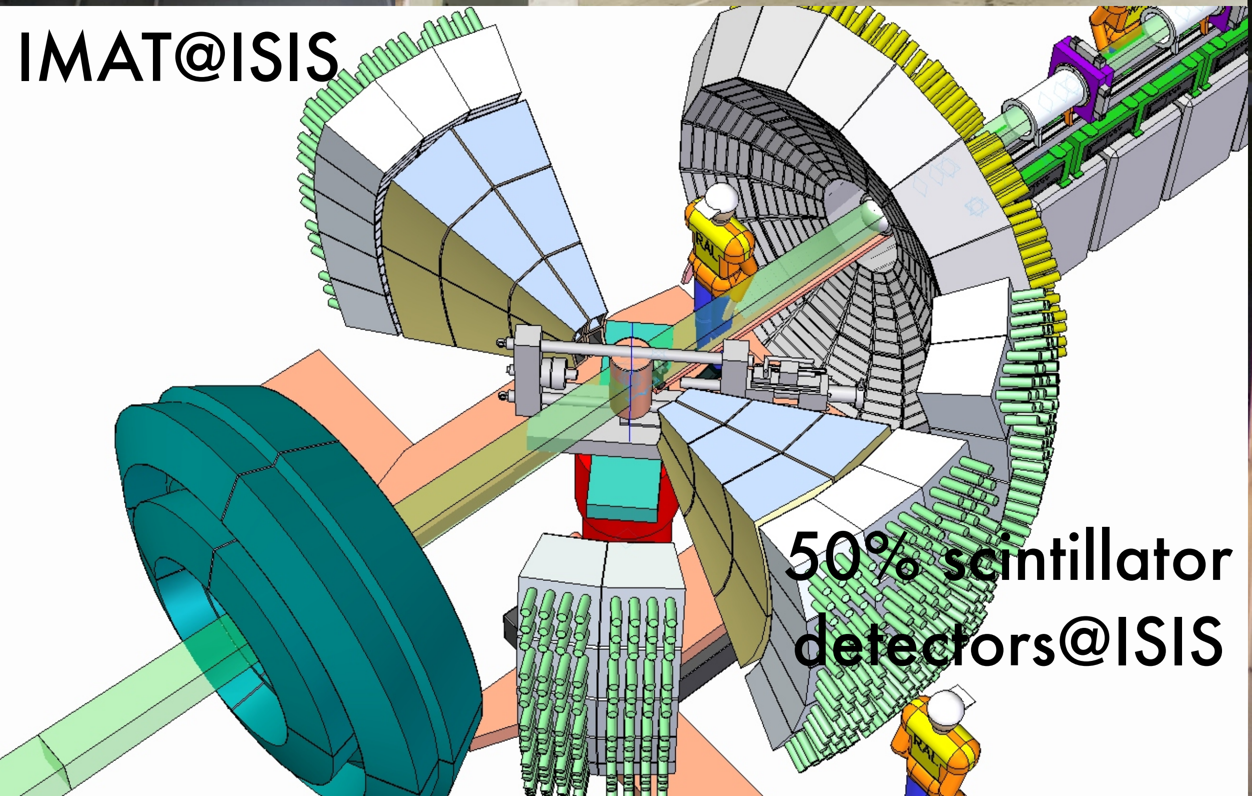
Shows scintillator plate with all fibers installed and connected to multi-anode photomultiplier mount.

Scintillator Neutron Detectors

POLARIS DETECTORS

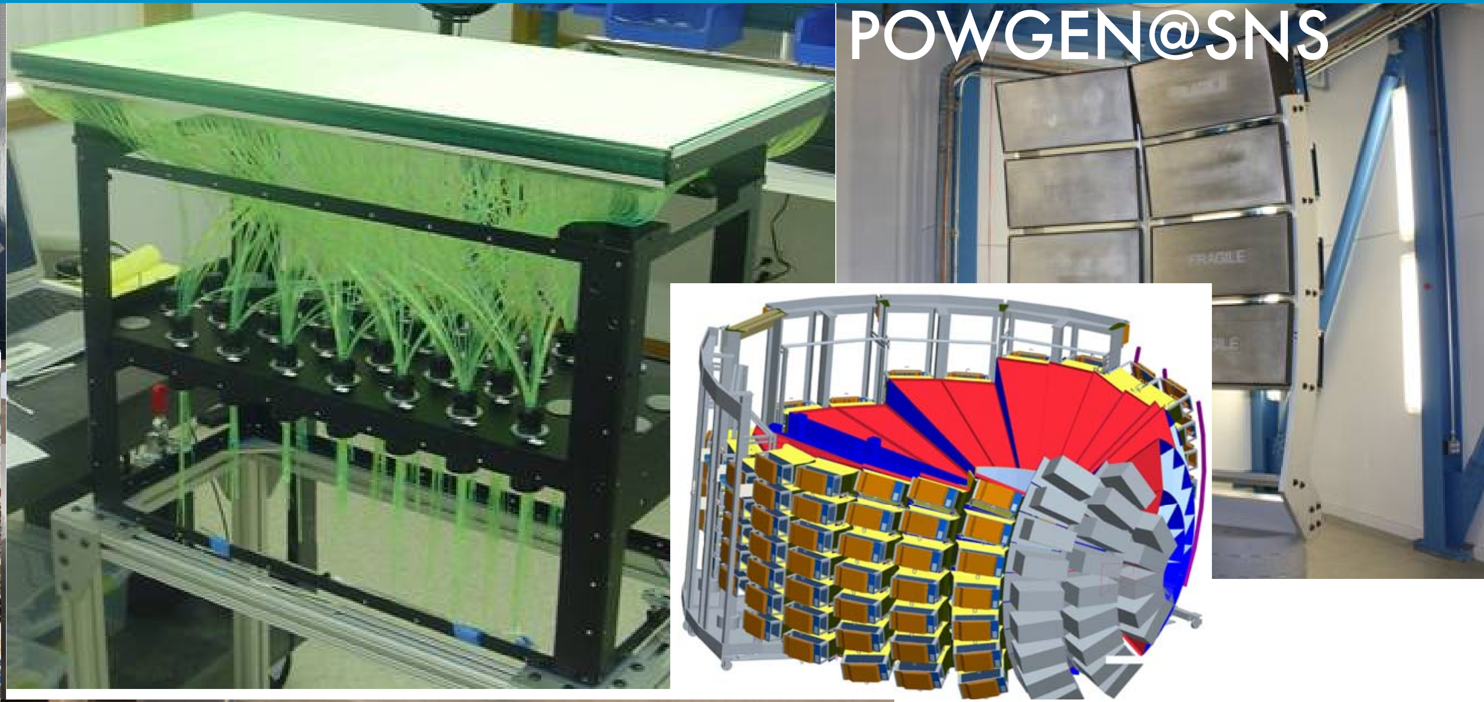


POLARIS @ISIS

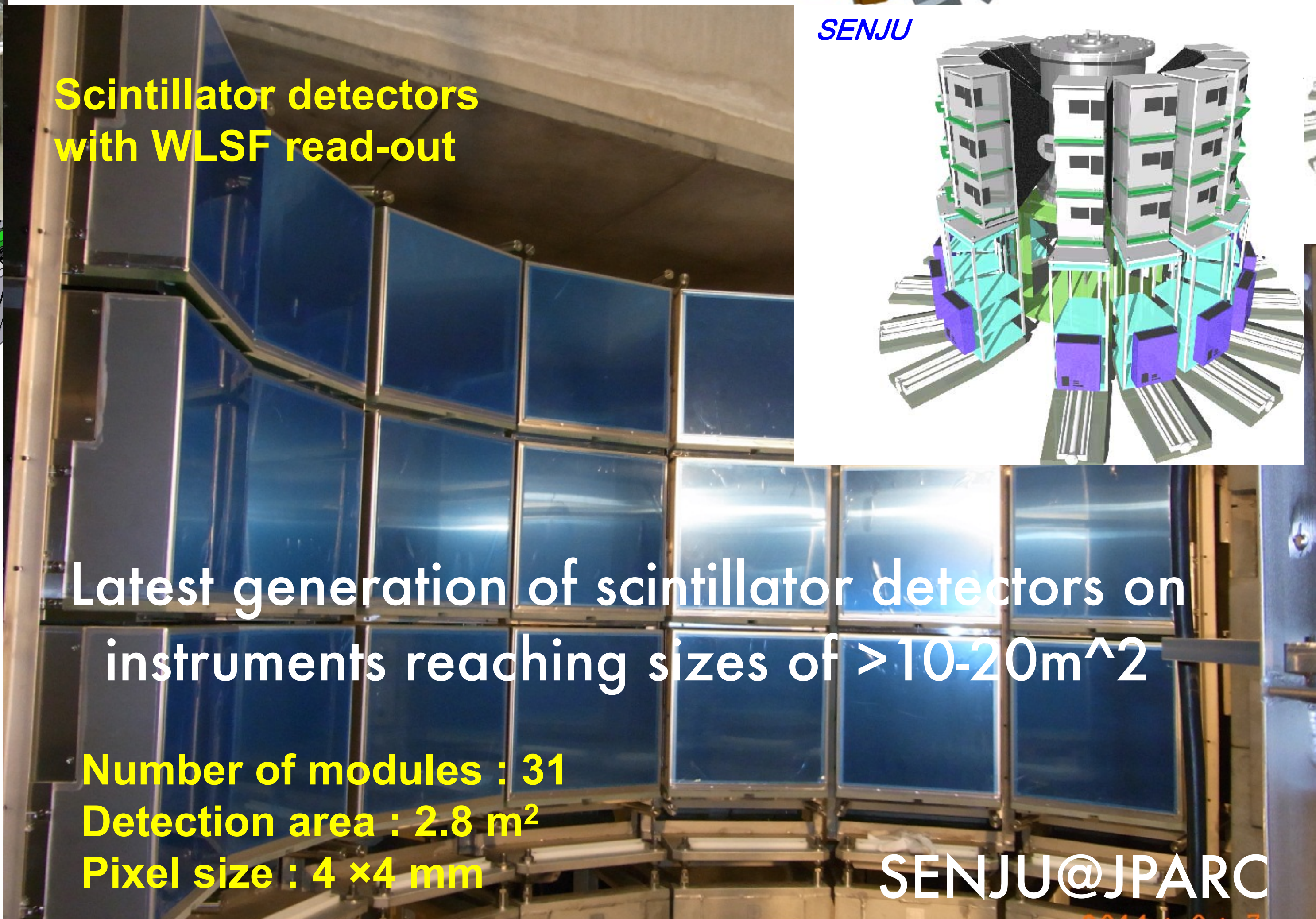


IMAT@ISIS

50% scintillator detectors@ISIS



POWGEN@SNS



SENJU

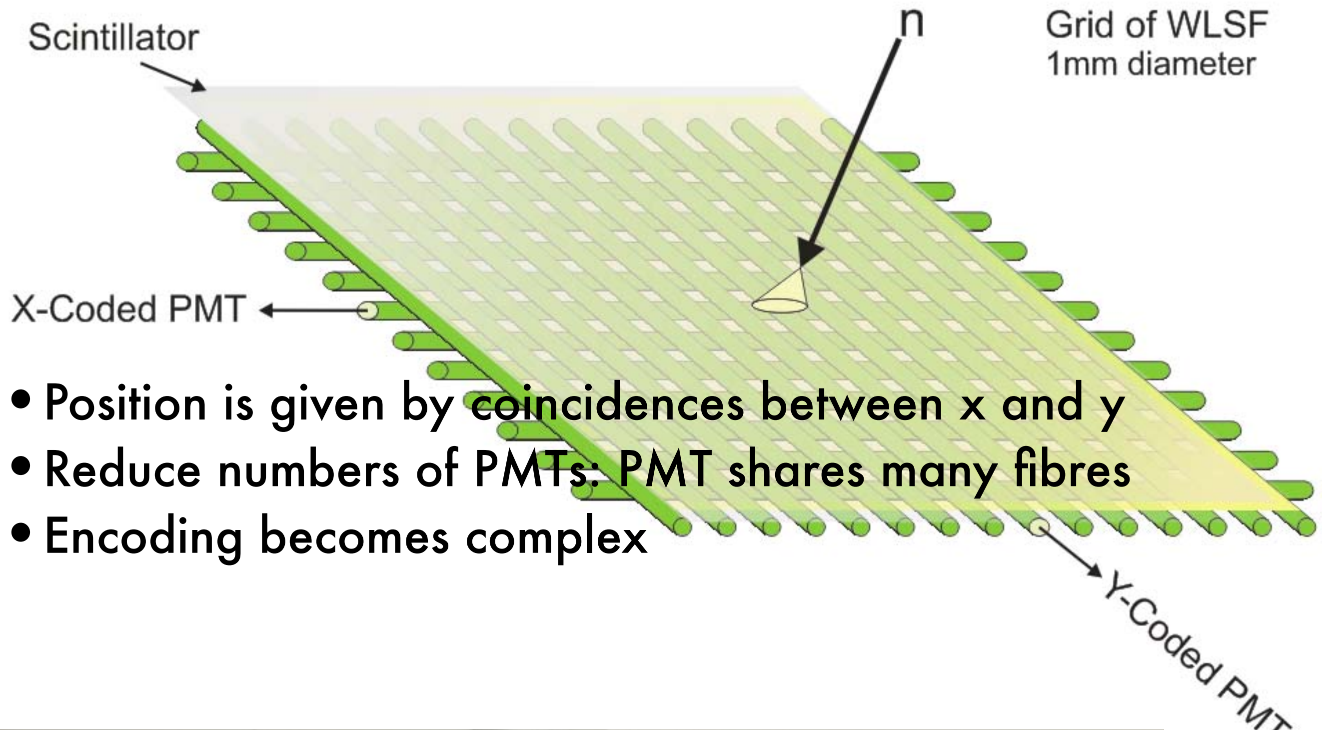
Scintillator detectors with WLSF read-out

Latest generation of scintillator detectors on instruments reaching sizes of >10-20m^2

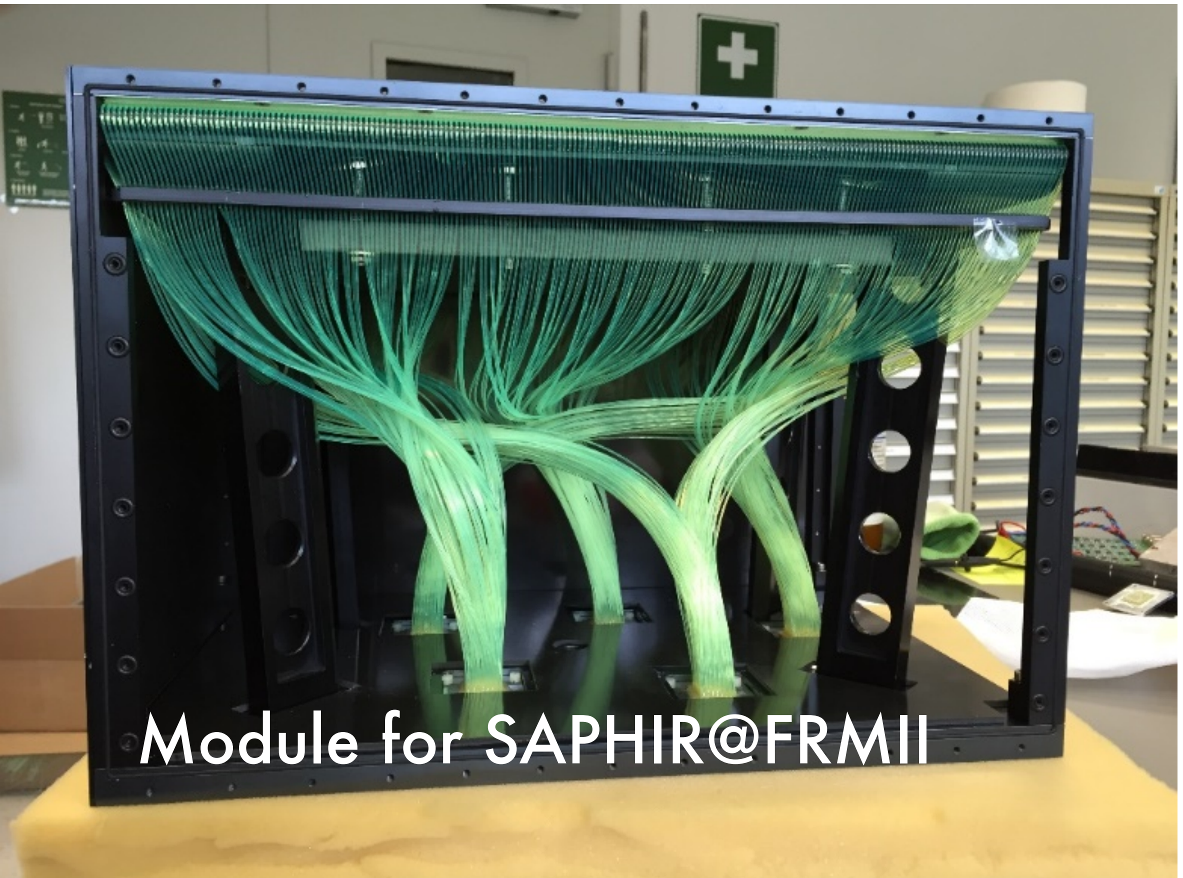
Number of modules : 31
Detection area : 2.8 m²
Pixel size : 4 ×4 mm

SENJU@JPARC

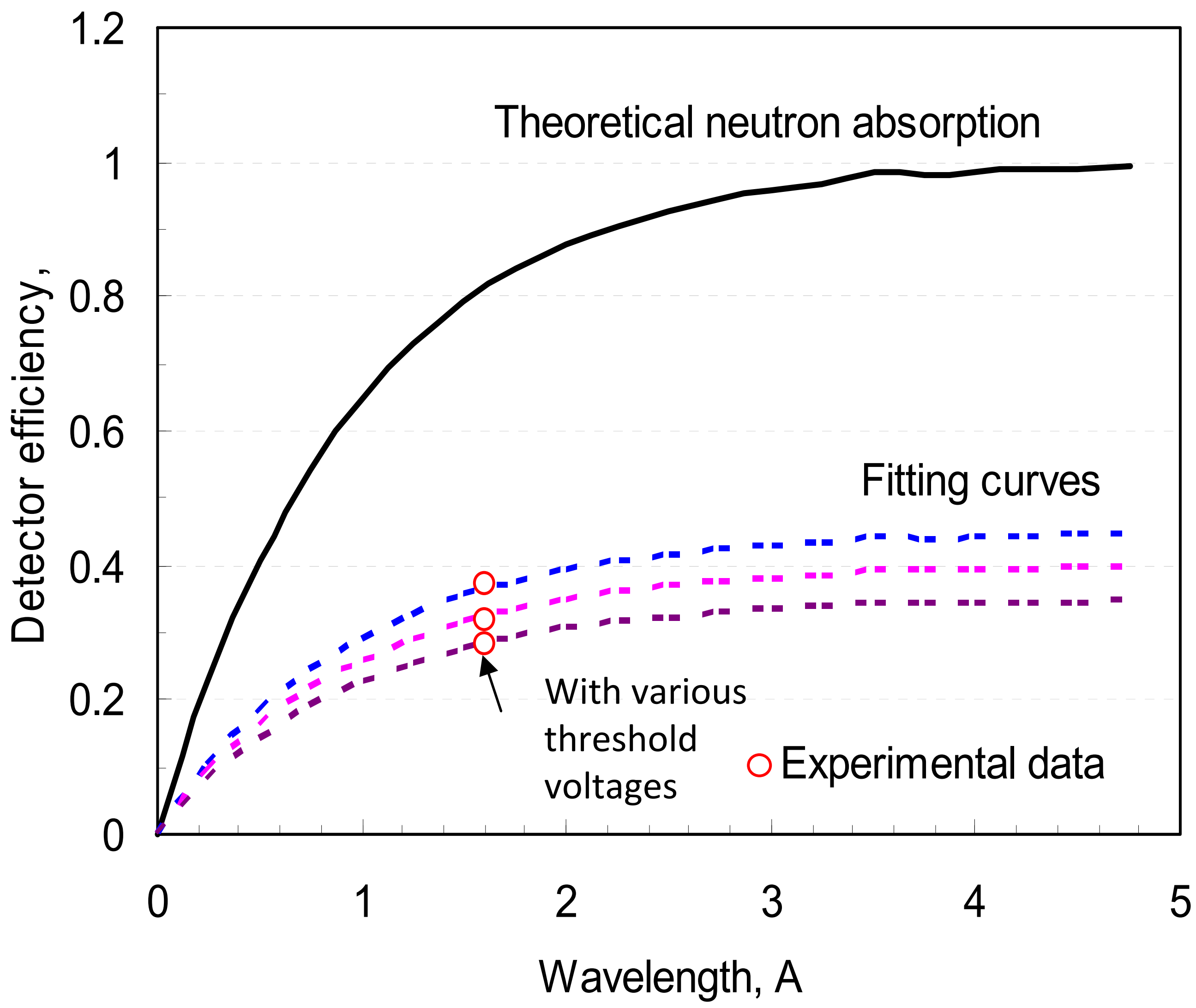
Neutron Scintillator Detectors



- Position is given by coincidences between x and y
- Reduce numbers of PMTs: PMT shares many fibres
- Encoding becomes complex



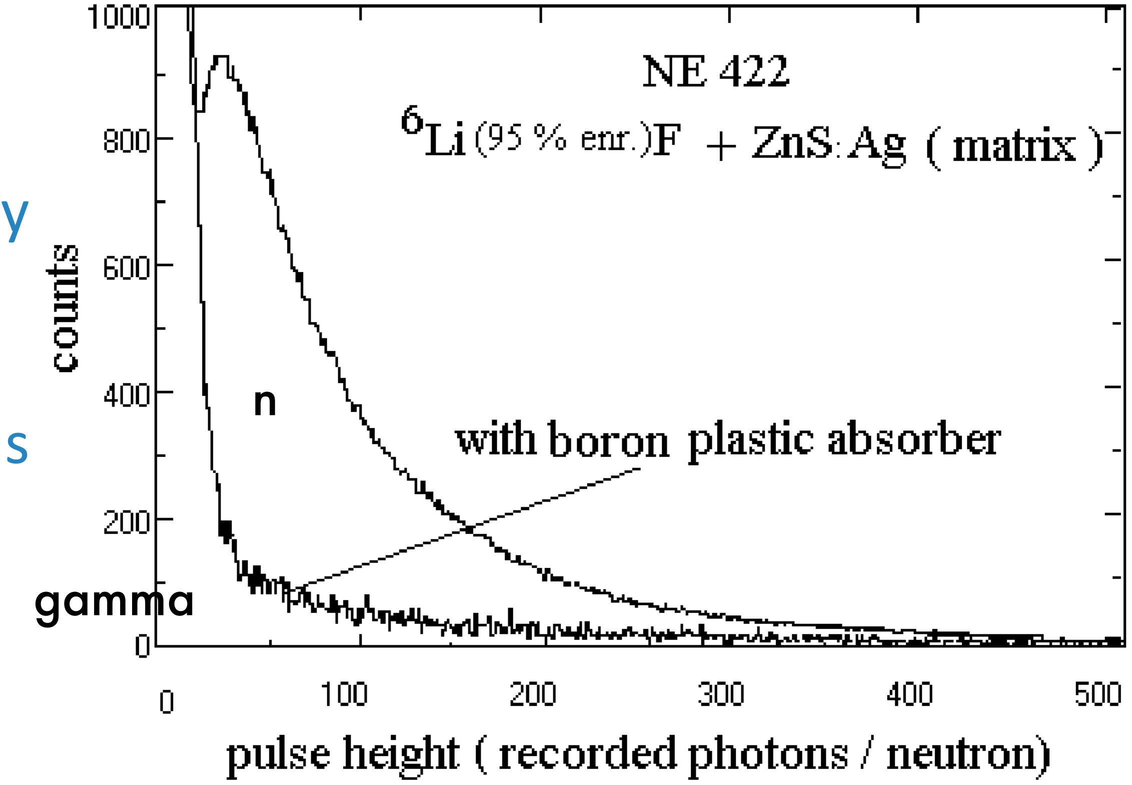
Module for SAPHIR@FRMII



- Scintillator typically used: ^{6}Li embedded in ZnS
- Scintillator detectors tend to be used for more thermal neutrons
- Efficiencies of 30-40% for thermal neutrons
- 2D position resolutions of few mm possible

Neutron Scintillator Detectors

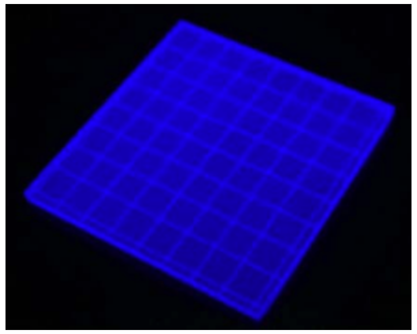
- Now pushing the limits of scintillator detector technology
  - Gamma/n pulse shape discrimination
  - Scintillation decay time (secondary >10us for ZnS)
- Big improvements need novel better scintillator materials or improvement in rate capability



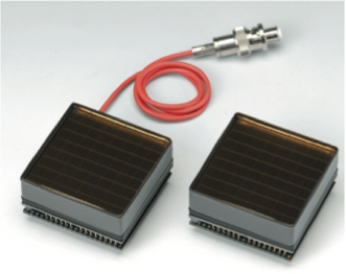
Develop a high-resolution neutron detector technique for enabling the construction of position-sensitive neutron detectors for high flux sources.

- high-flux capability for handling the peak-flux of up-to-date spallation sources (x 20 over current detectors)
- high-resolution of 3 mm by single-pixel technique, below by interpolation
- high detection efficiency of up to 80 %

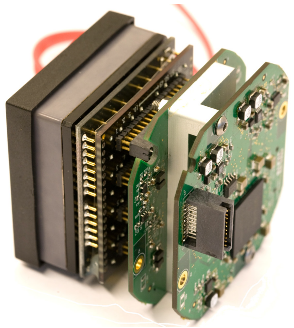
Grooved Li glass



\+ MA-PMT



\+ IDEAS ROSMAP

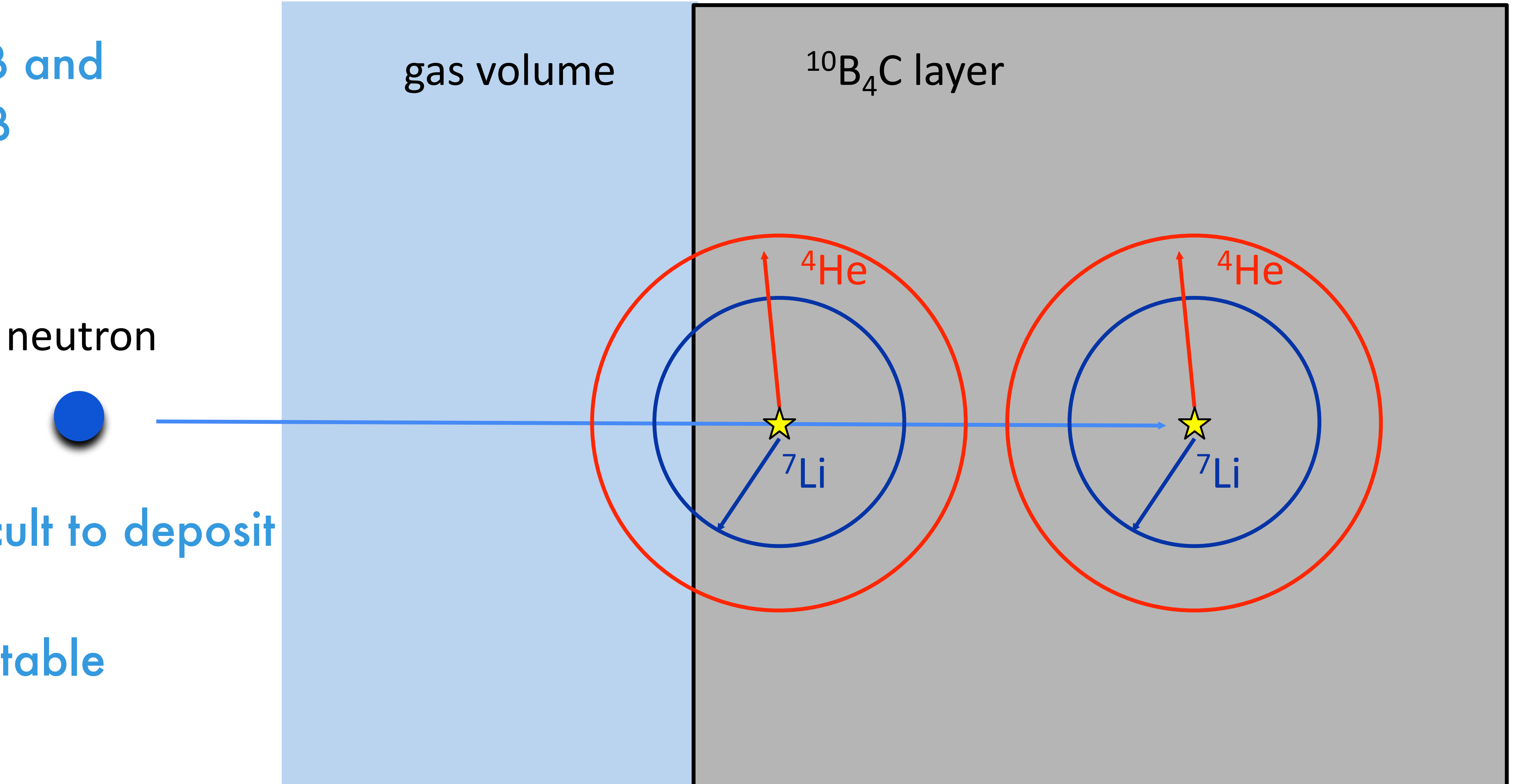


^{10}Boron-based Thin Film Gaseous Detectors

$$\begin{aligned} {}^{10}B + n \rightarrow {}^{7}Li^{*} + {}^{4}He \rightarrow {}^{7}Li + {}^{4}He + 0.48MeV\,\gamma\text{-ray} + 2.3\ \ MeV & \quad (94\%) \\ \rightarrow {}^{7}Li + {}^{4}He \qquad\qquad + 2.79\,MeV & \quad (6\%) \end{aligned}$$

Efficiency limited at ~5% (2.5Å) for a single layer

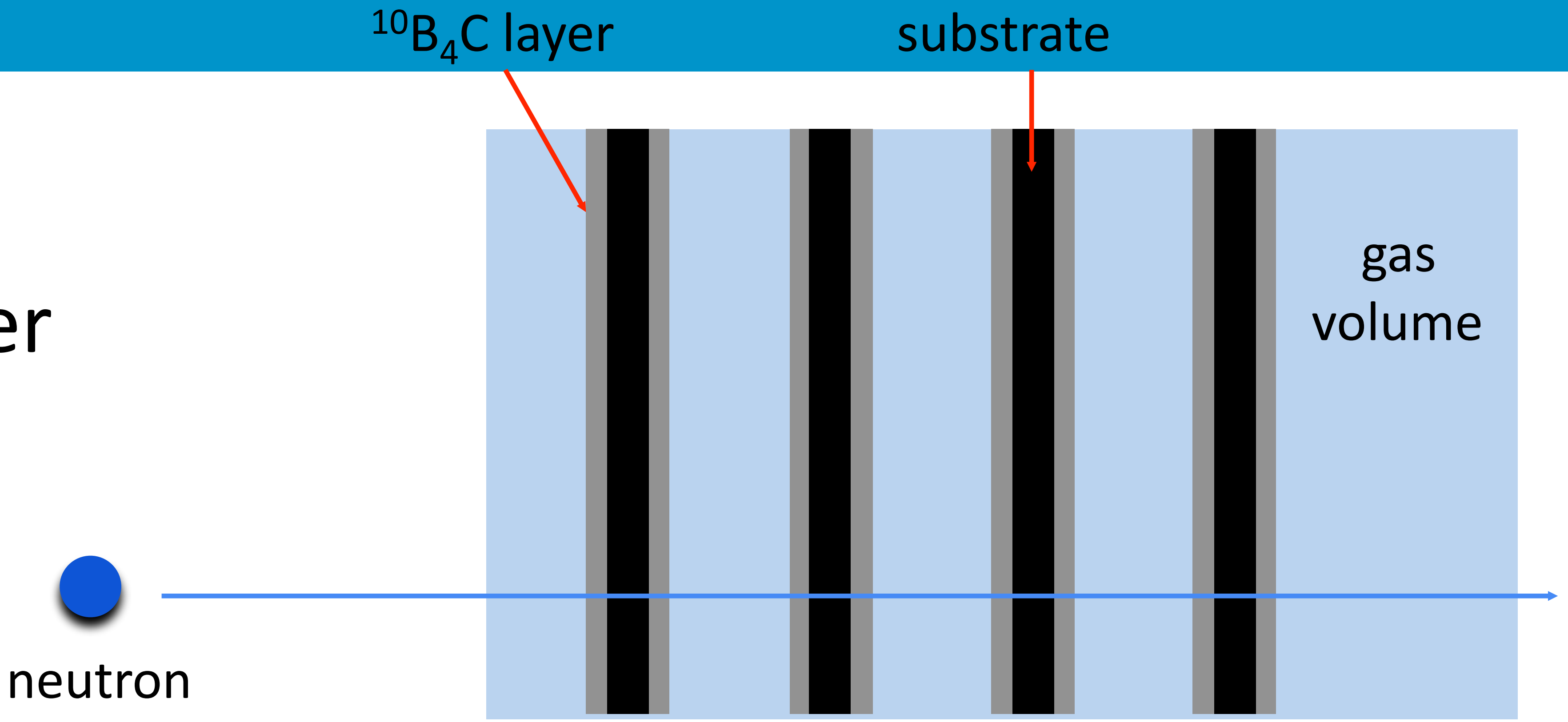
- ^{nat}B contains
  80 at.% ^{11}B and
  20 at.% ^{10}B



- Boron is difficult to deposit
- Use $^{10}B_4C$
- Conductive, stable

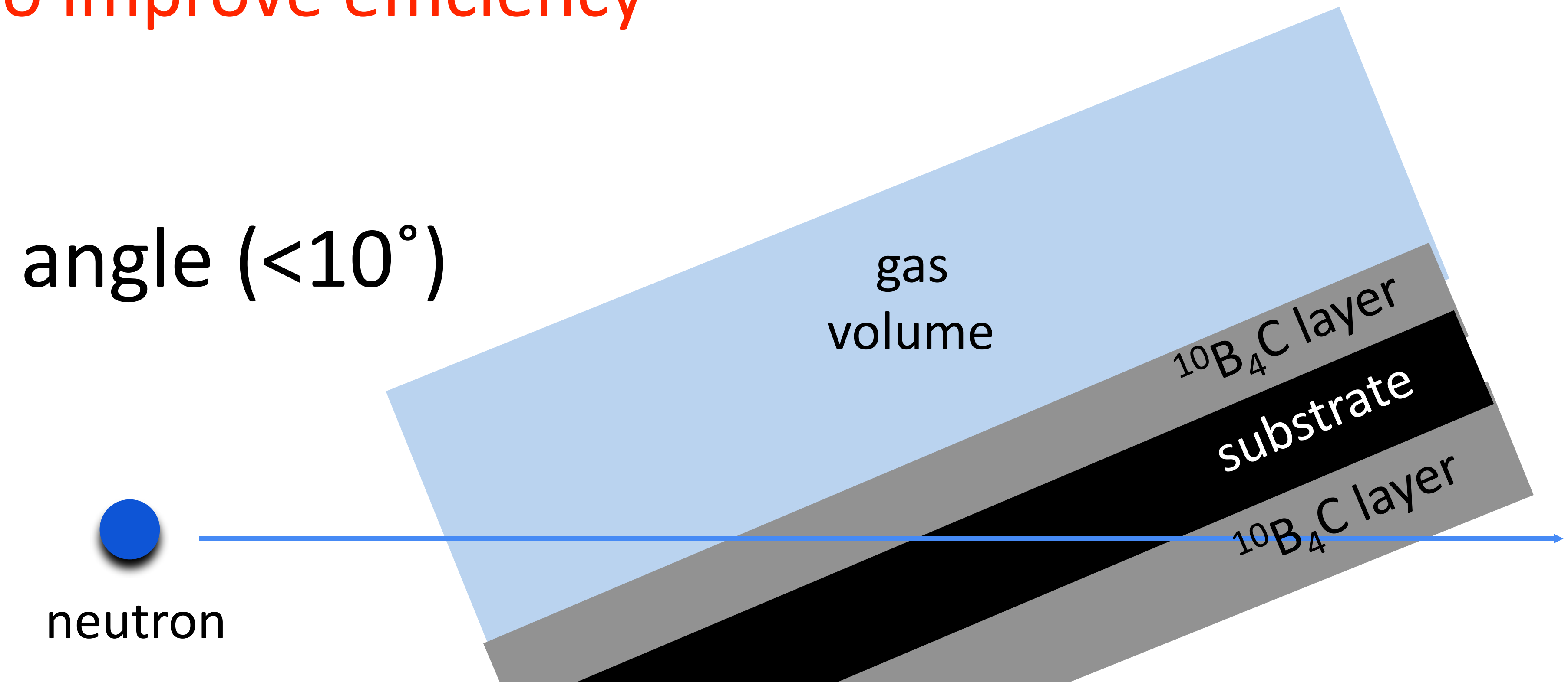
Enhancing the efficiency of ^{10}B-based Neutron Detectors

① Multi layer



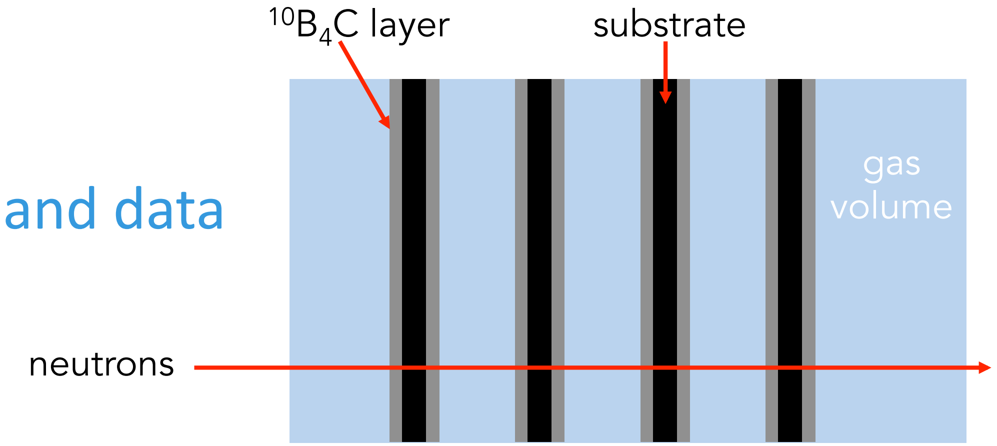
Generic approaches to improve efficiency

② Grazing angle (<10˚)



Efficiency of ^{10}B Detectors: Perpendicular Geometry

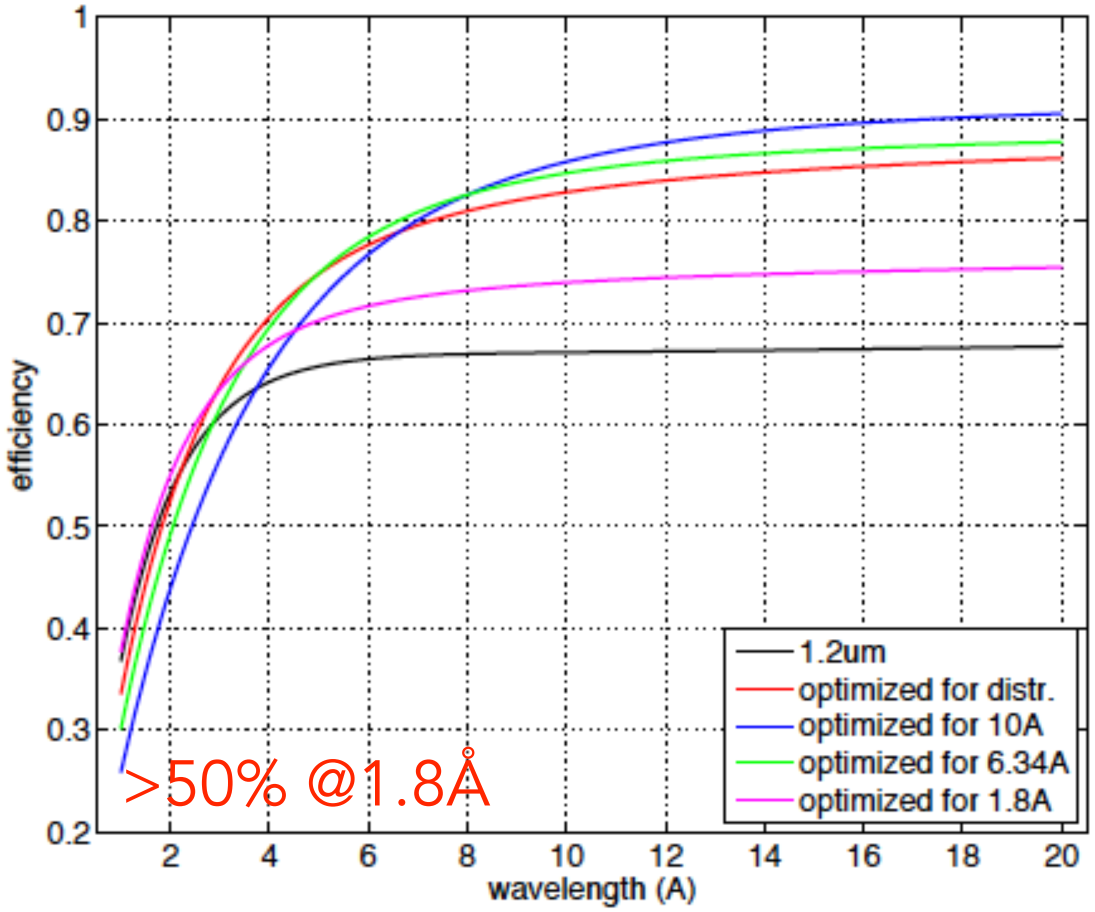
- Single layer is only ca.5%
- Calculations done by many groups
- Analytical calculations extensively verified with prototypes and data
- Details matter: just like for ^{3}He



- Multilayer configuration (example):

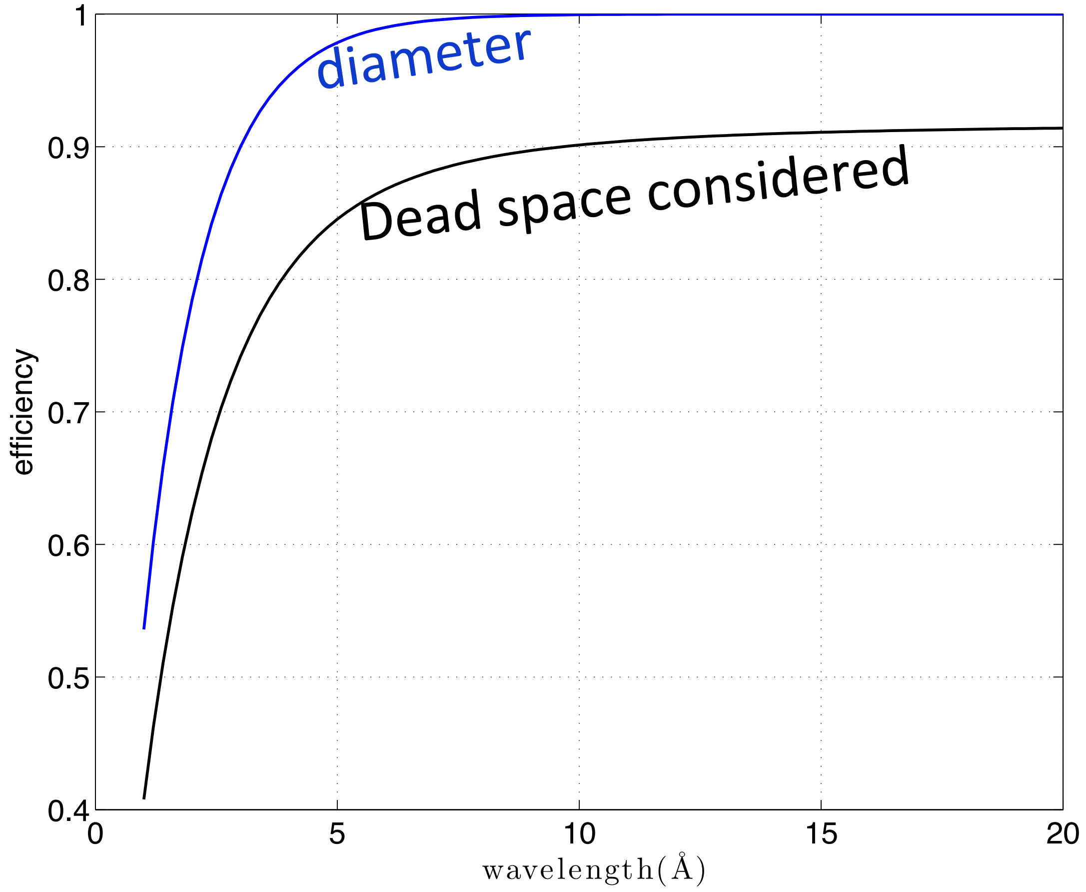
JINST 8 (2013) P04020

Multi-Grid



>50% @1.8Å

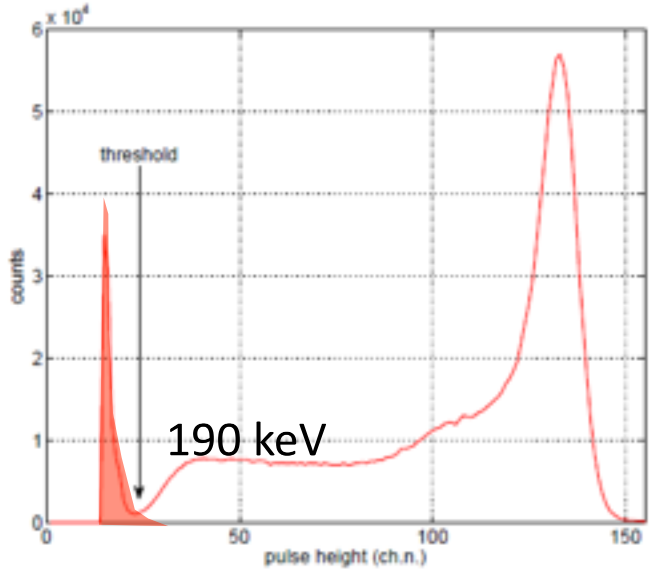
^{3}He tubes – 1 inch – 4.75 bar



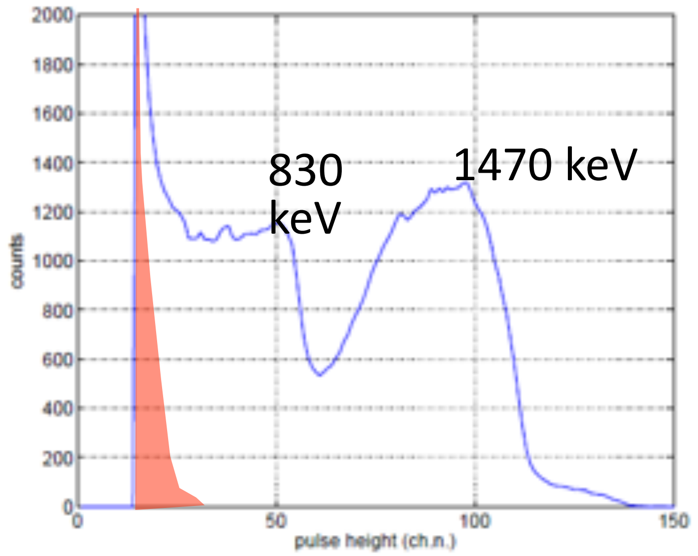
diameter

Dead space considered

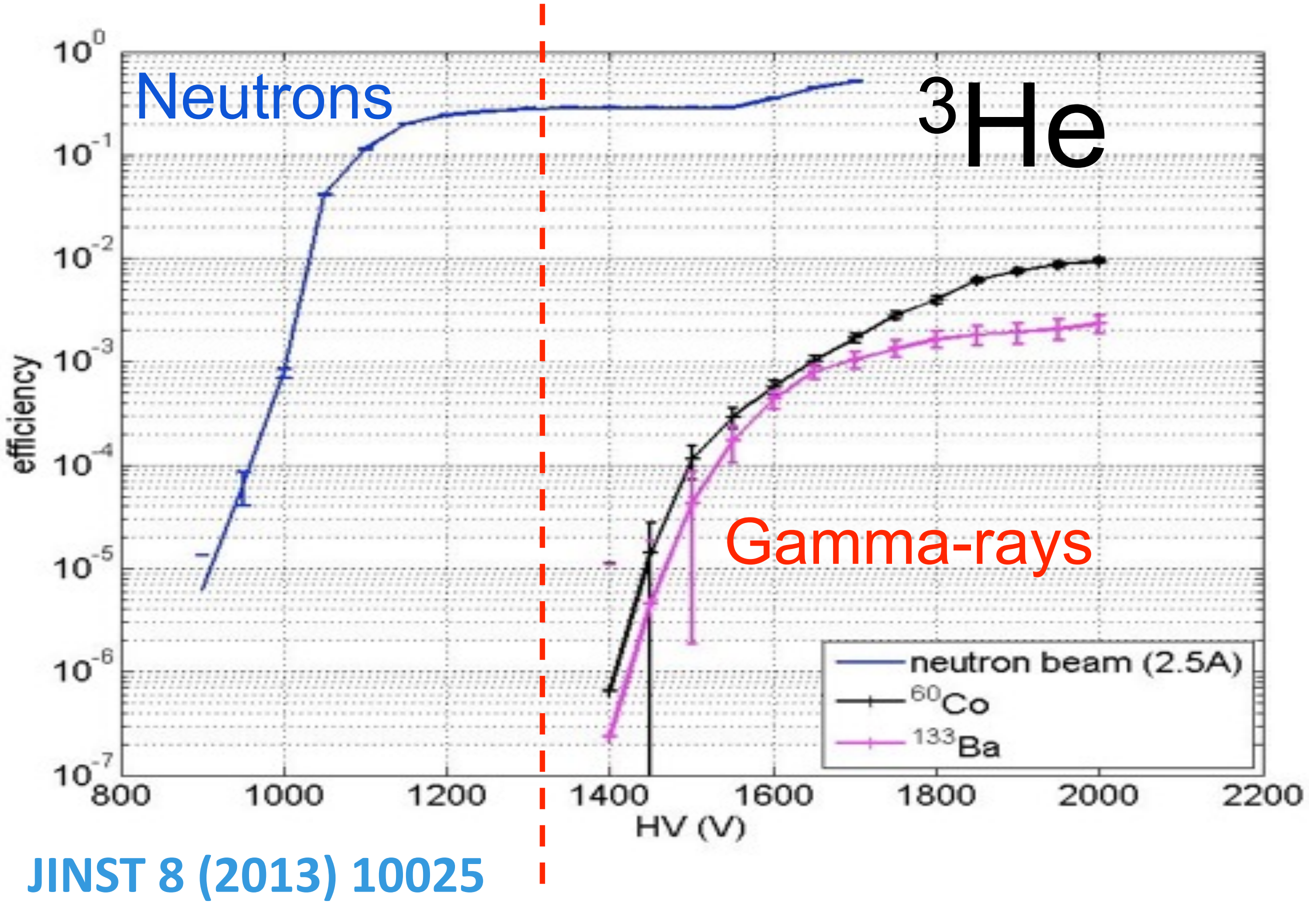
Background - Gamma Sensitivity



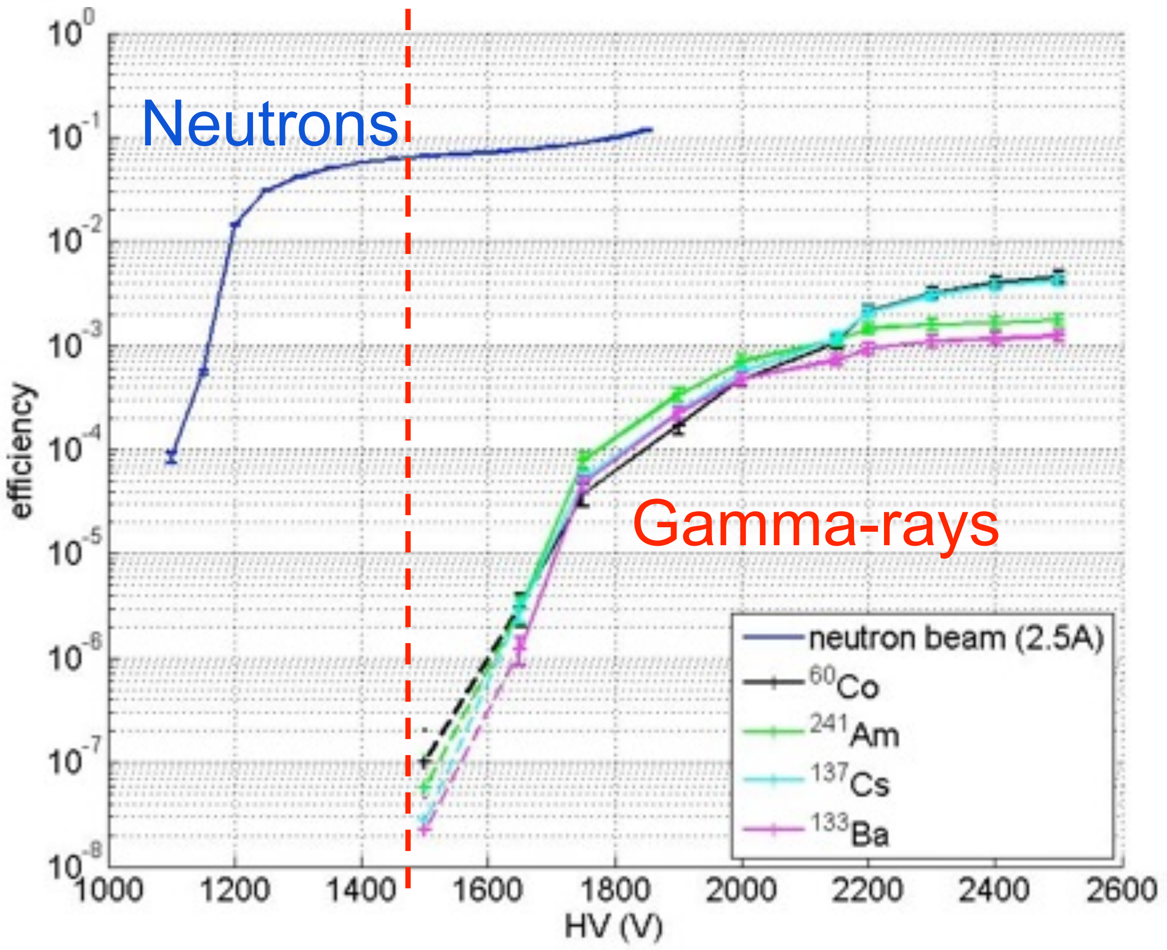
$<10^{-6}$



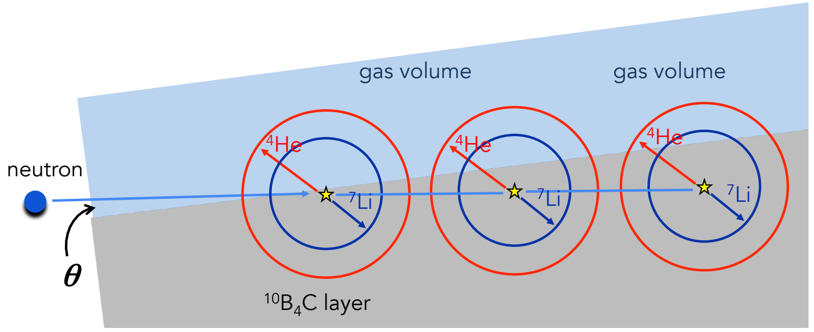
$<10^{-6}$

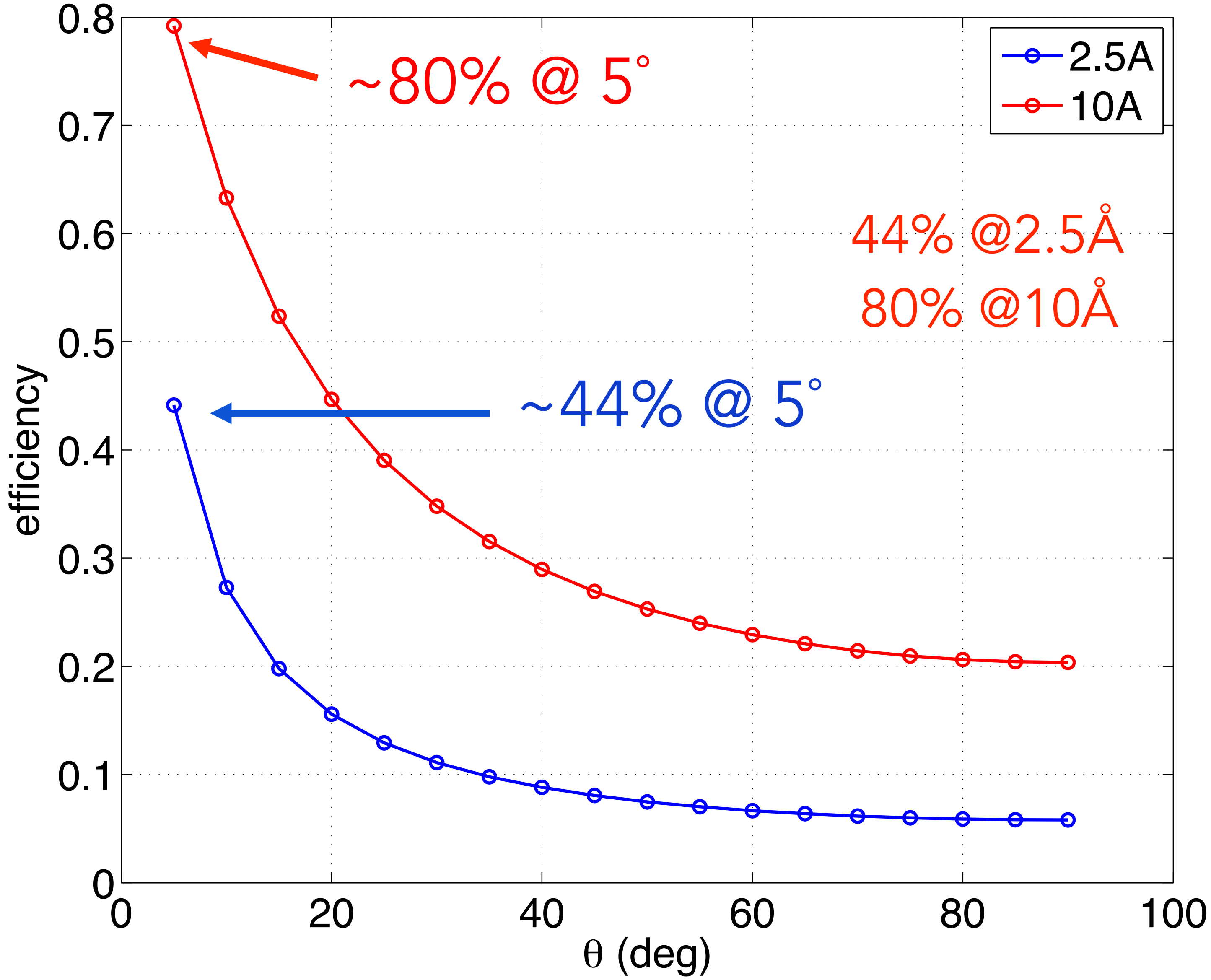


JINST 8 (2013) 10025



Efficiency of ^{10}Boron Detectors: Inclined Configuration





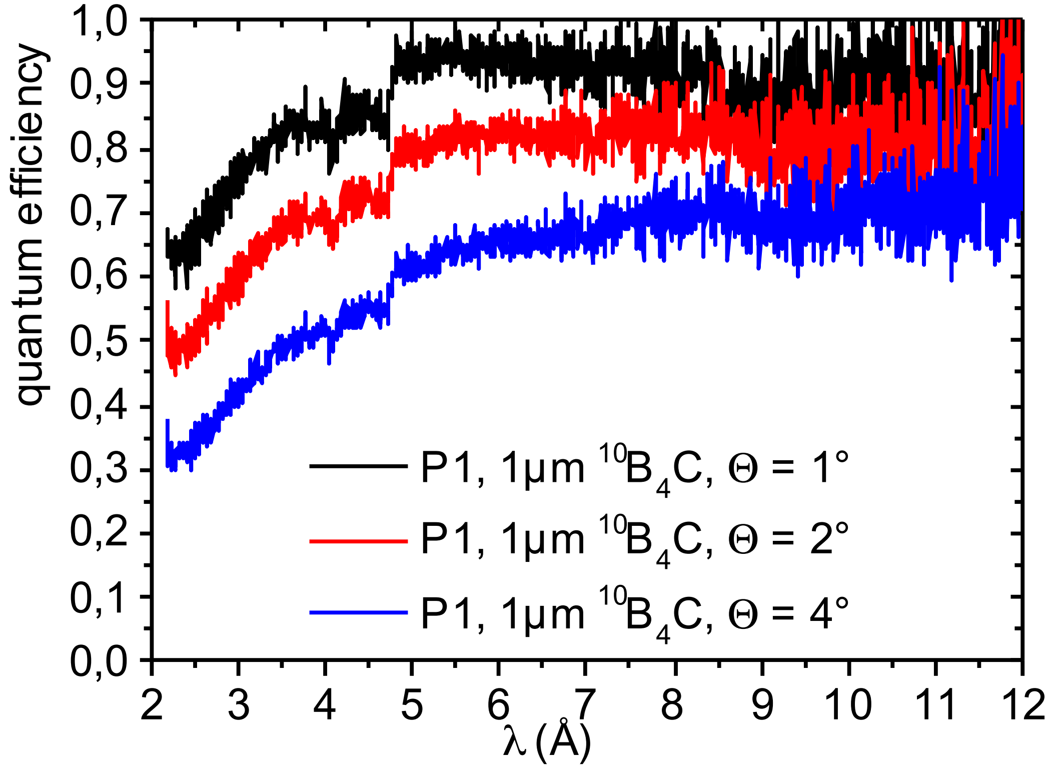
~80% @ 5°

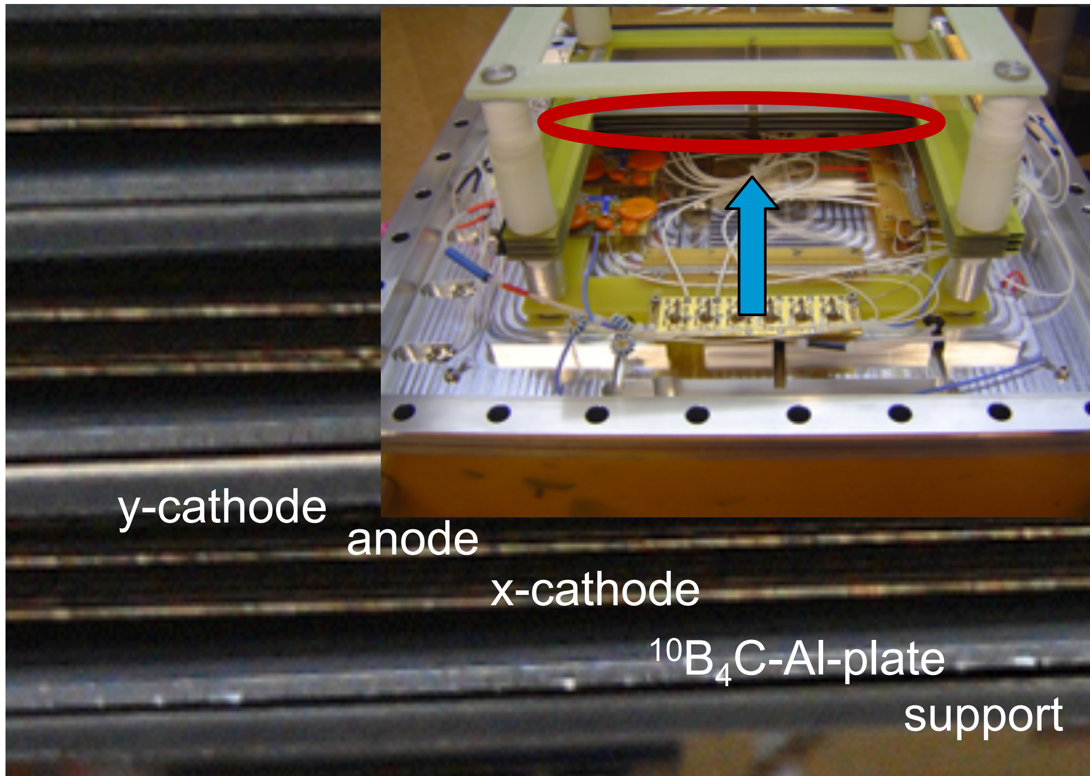
44% @2.5Å
80% @10Å

~44% @ 5°

F. Piscitelli, PhD Thesis, U.Perugia (2014)

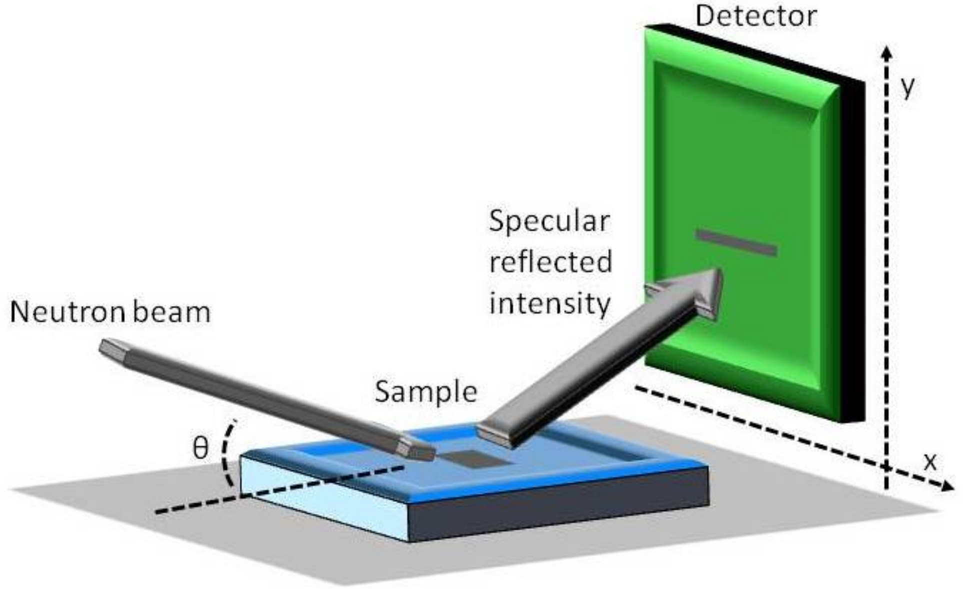
smaller inclined angles: higher efficiency

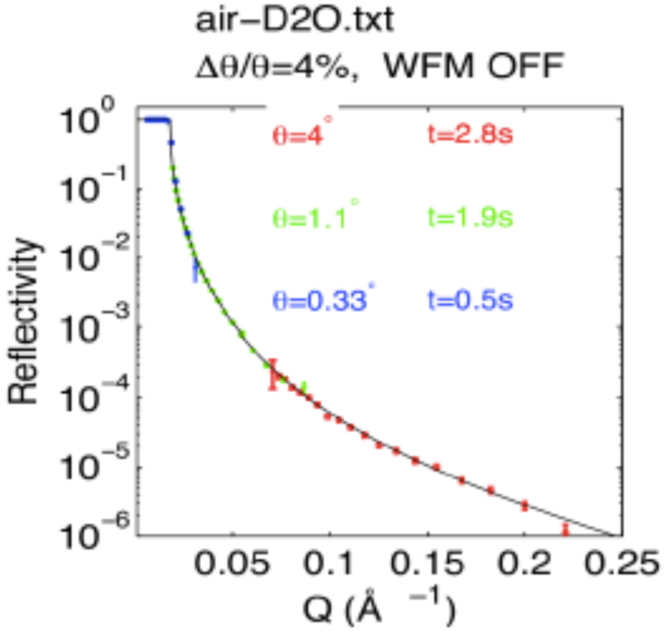




Neutron Reflectometry: A Rate Challenge

- Rate requirements is high:
  - Intensity of new sources
  - Time structure of pulse
  - Advanced design instruments





ESS requirements

area $(mm \times mm)$	spatial resolution $(mm \times mm)$	global rate (s^{-1})	local rate $(s^{-1}mm^{-2})$
500×500	$[\leq 0.5, 2] \times 2$	$[5, 100] \cdot 10^5$	$[5, 300] \cdot 10^2$

x10

x100

The state of the art

area $(mm \times mm)$	spatial resolution $(mm \times mm)$	global rate (s^{-1})	local rate $(s^{-1}mm^{-2})$
500×500	1×2	$100 \cdot 10^5$	300

^{3}He technology

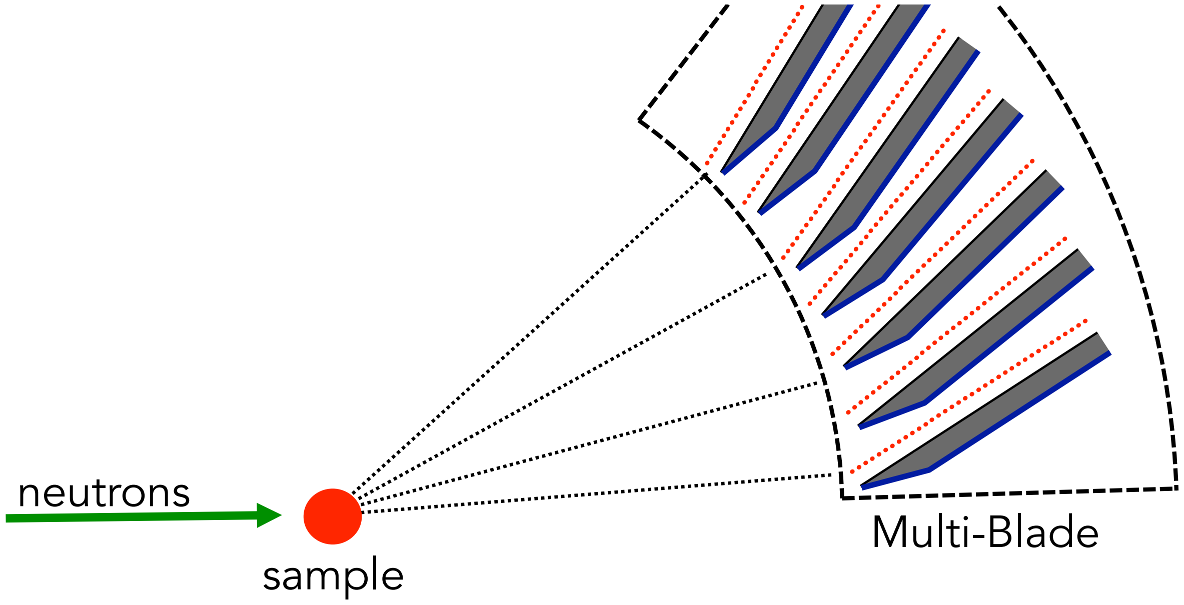
x1

x10

Multi-Blade

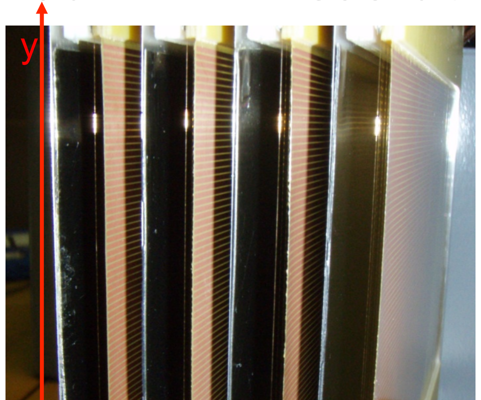
area $(mm \times mm)$	spatial resolution $(mm \times mm)$	global rate (s^{-1})	local rate $(s^{-1}mm^{-2})$
	0.3 x 4		>1000

^{10}B technology



Multi-blade design:

- High rate capability
- Sum-mm resolution



Multi-Blade Design

BrightnESS

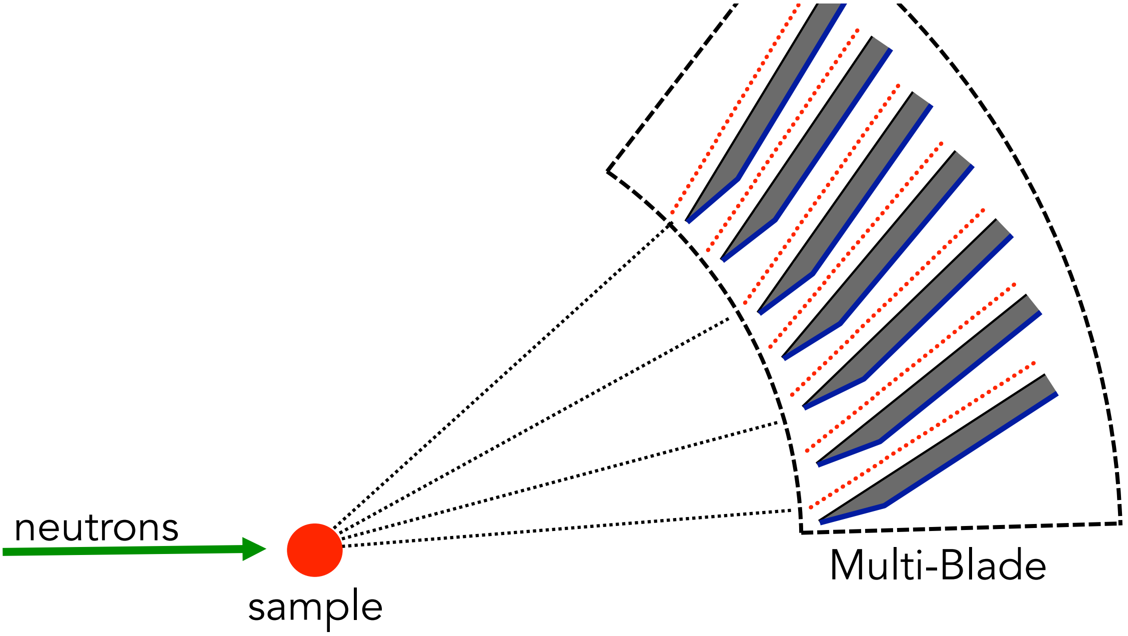
EUROPEAN SPALLATION SOURCE

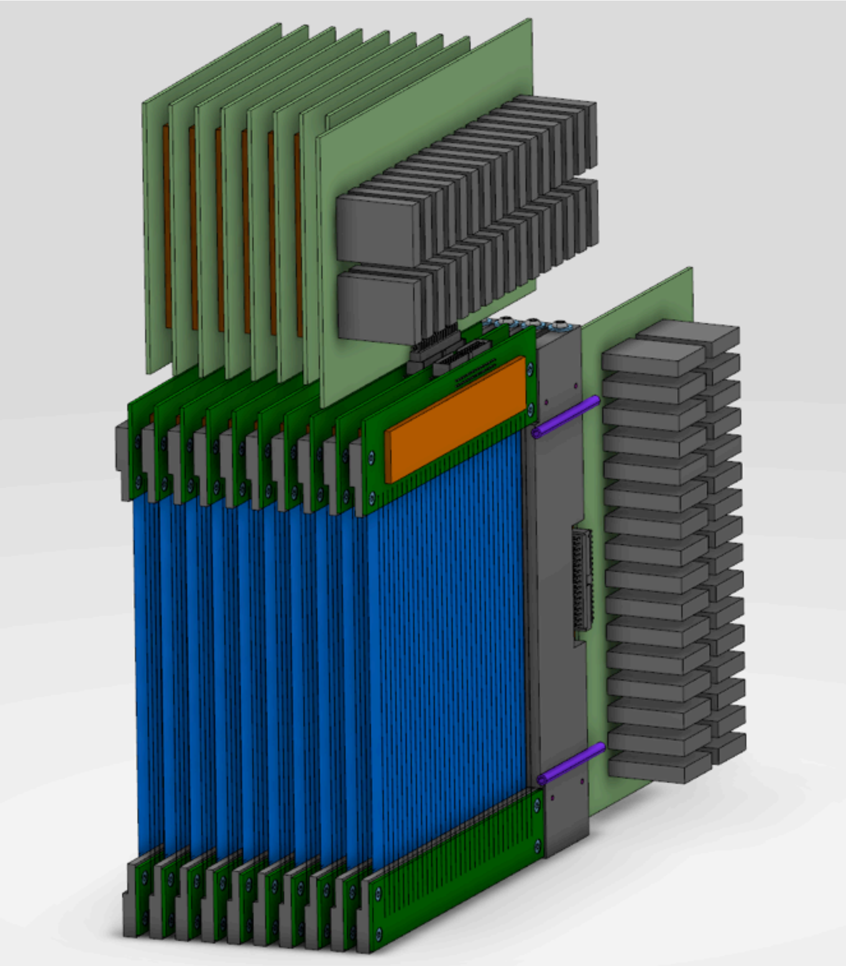
LUND UNIVERSITY

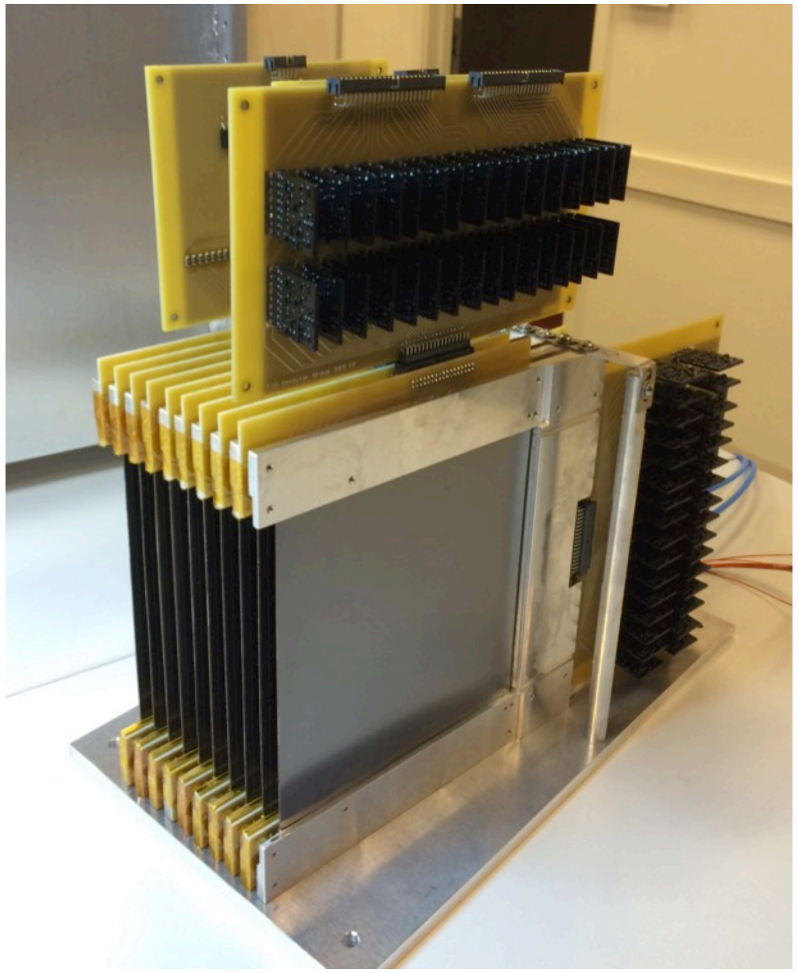
Wigner Research Institute

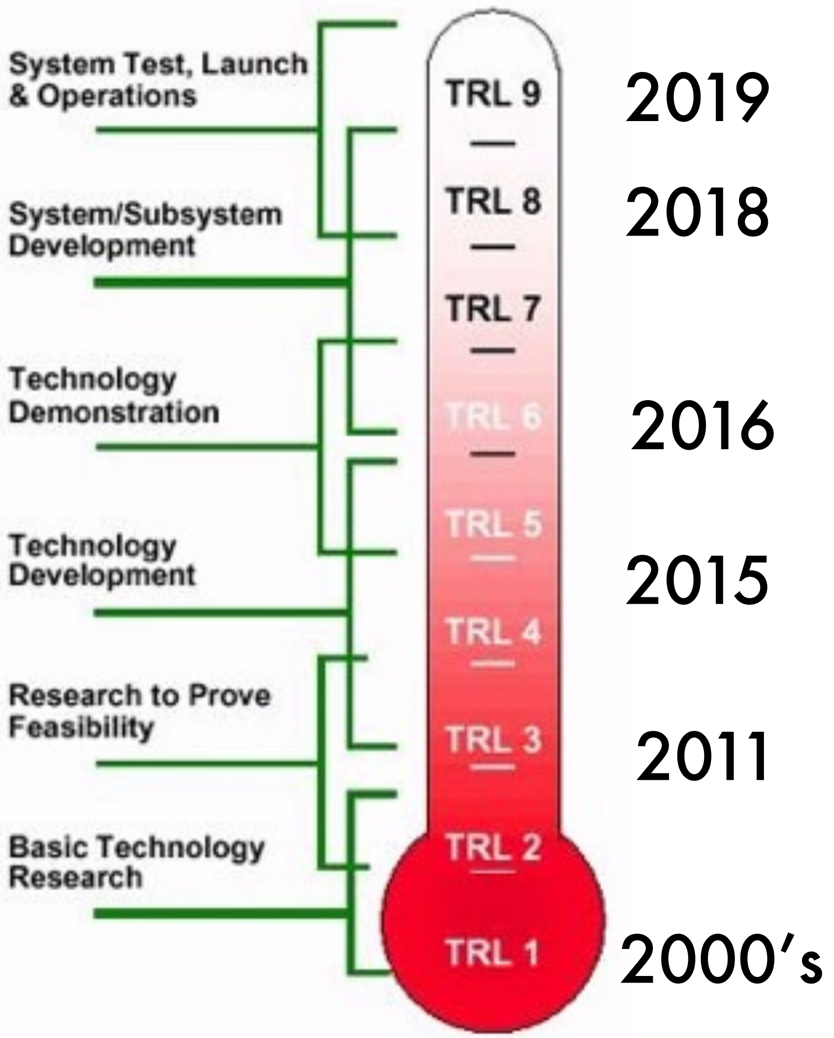
Budapest Neutron Centre

- Design simple: *"KISS"*
- Modular
- Cheap
- Make design available
- *"Open Source Hardware"*









System Test, Launch & Operations — TRL 9 — 2019

System/Subsystem Development — TRL 8 — 2018

TRL 7

Technology Demonstration — TRL 6 — 2016

Technology Development — TRL 5 — 2015

TRL 4

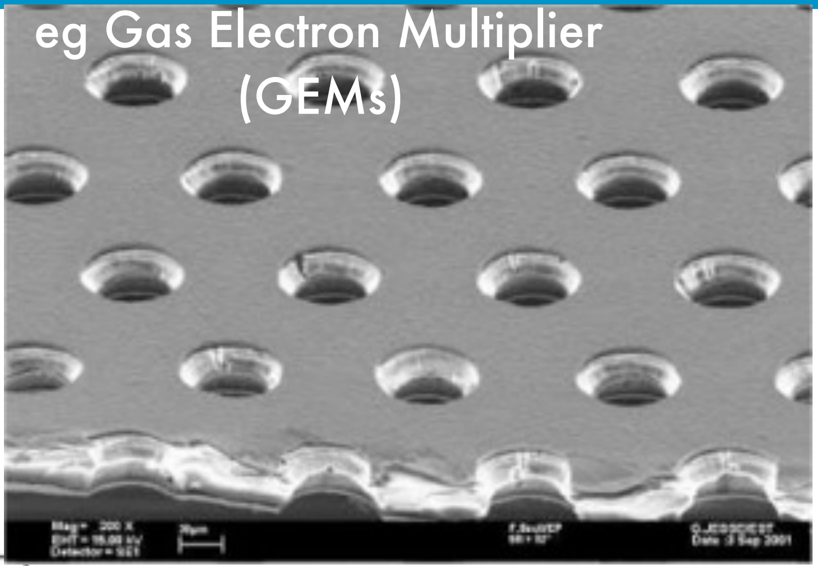
Research to Prove Feasibility — TRL 3 — 2011

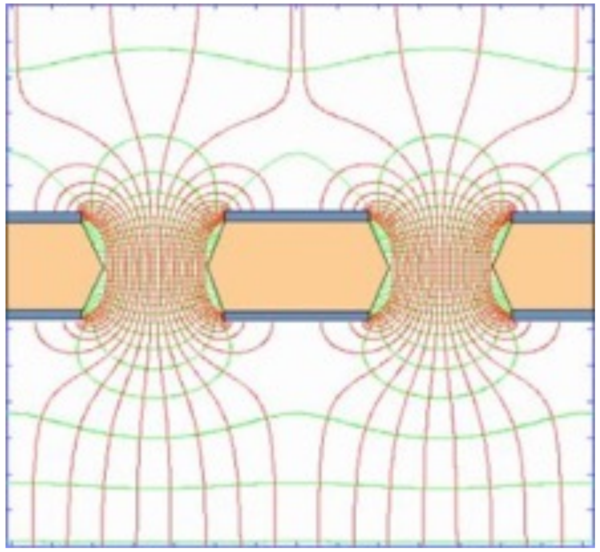
TRL 2

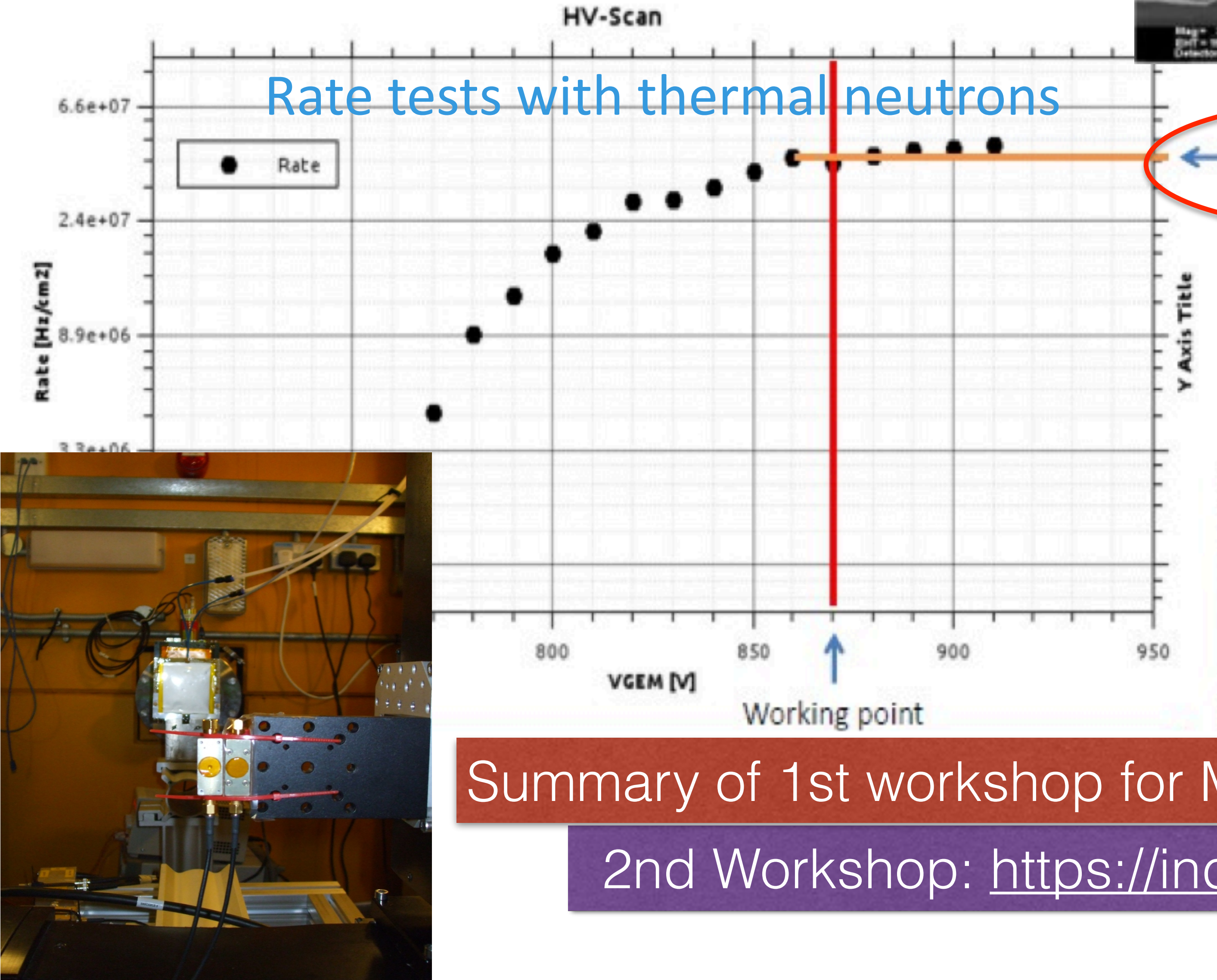
Basic Technology Research — TRL 1 — 2000's

Micropattern Gaseous Detectors

- Field started by A Oed at the ILL with the micro-strip gas chamber (MSGC) in 1988
- Now widespread: many variants
- Potentially very good resolution and very high rate capability


eg Gas Electron Multiplier (GEMs)



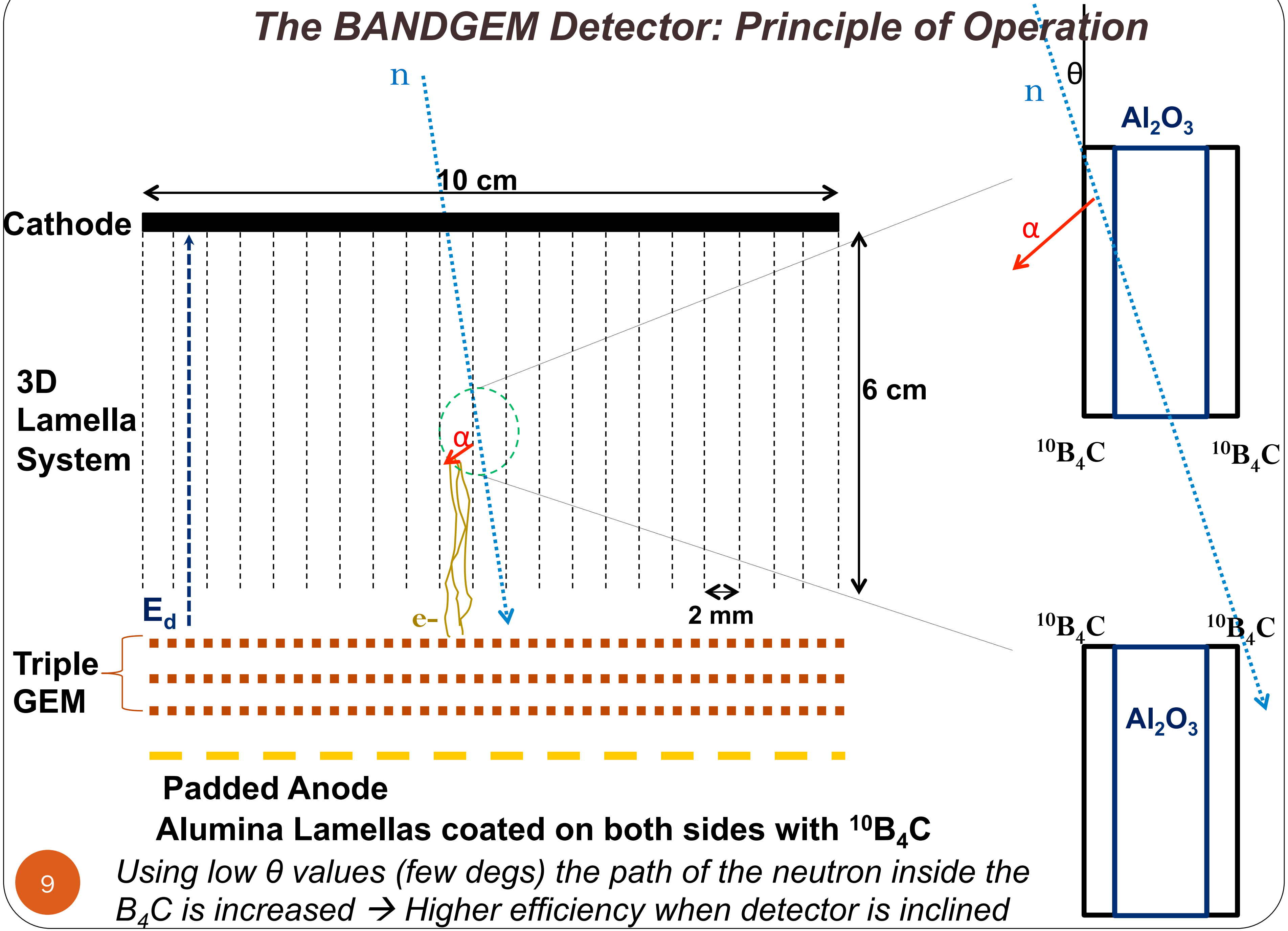


- Growing interest for applications for neutron detection
- 2 workshops organised by CERN RD51 Collaboration (with HEPTECH) on Neutron Detection using MPGDs

Summary of 1st workshop for MPGDs for neutron detection: arXiv:1410.0107

2nd Workshop: https://indico.cern.ch/event/365380/ arXiv:1601.01534

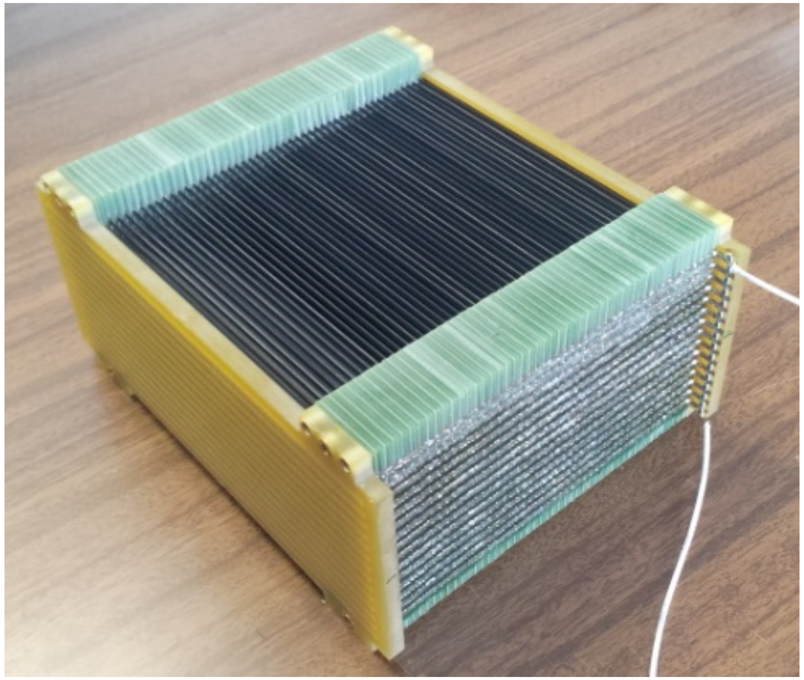
The BANDGEM Detector: Principle of Operation



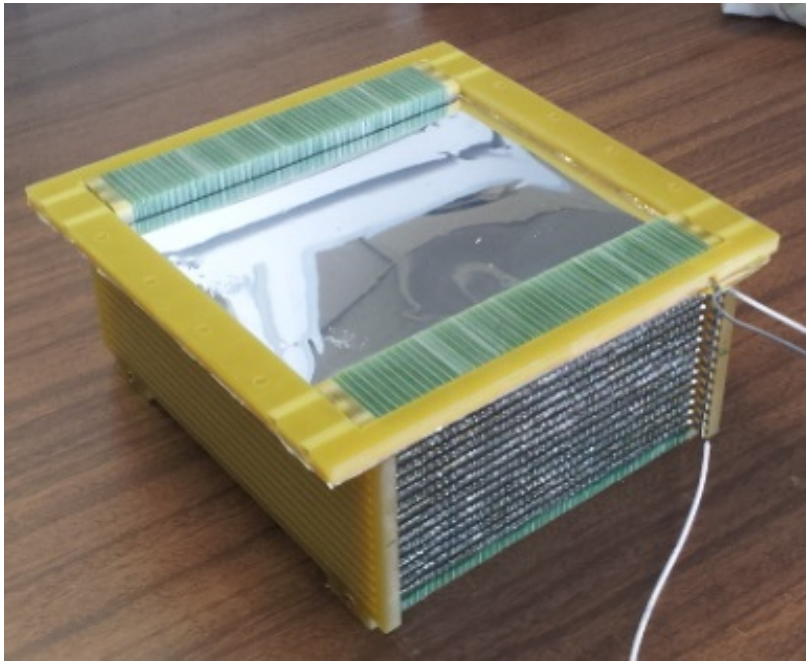
Alumina Lamellas coated on both sides with $^{10}B_4C$

Using low θ values (few degs) the path of the neutron inside the B_4C is increased → Higher efficiency when detector is inclined

BAND-GEM DETECTOR ASSEMBLY

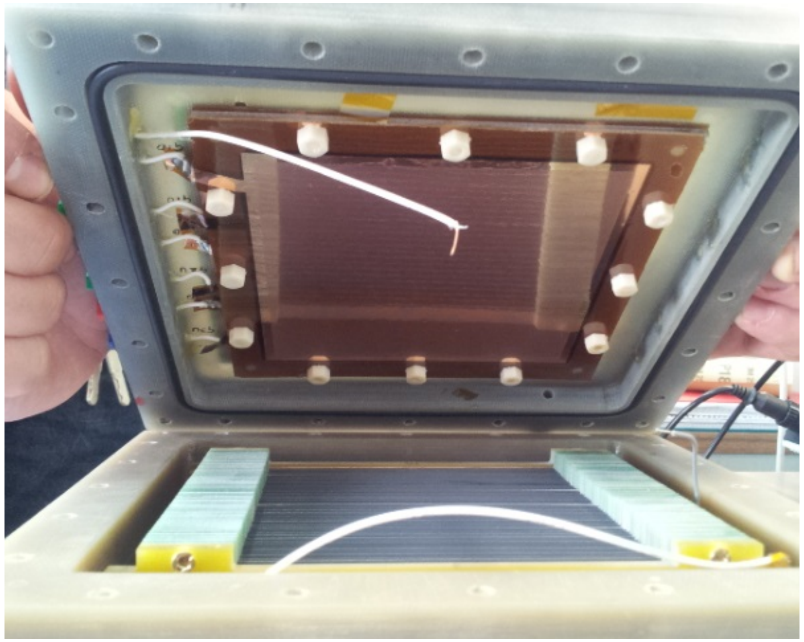


The full Lamella System.

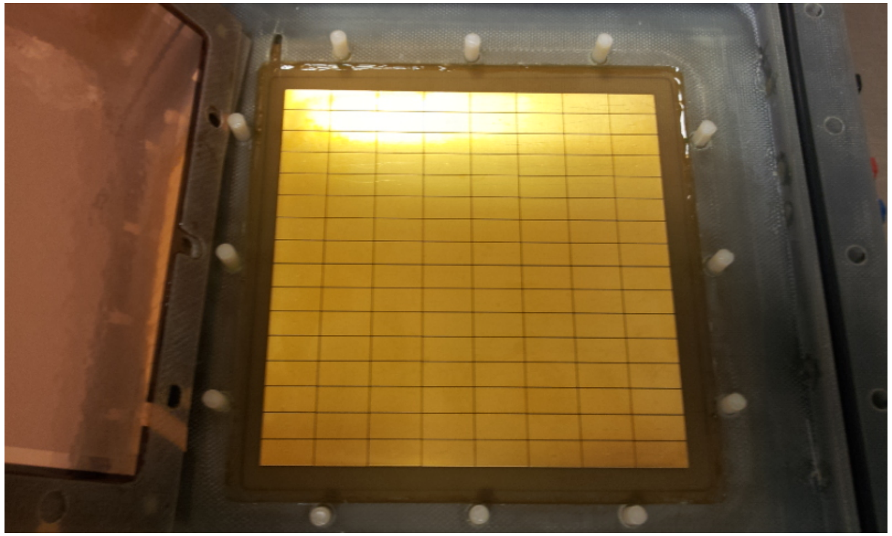


Aluminium cathode
mounted on top

BAND-GEM DETECTOR ASSEMBLY (cont'd)

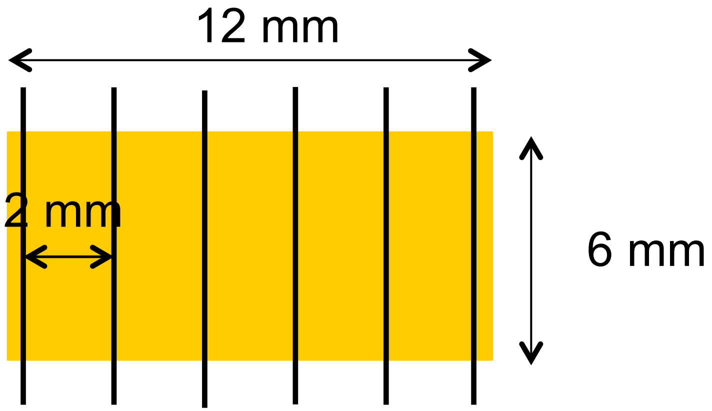


Assembly with Triple GEM detector



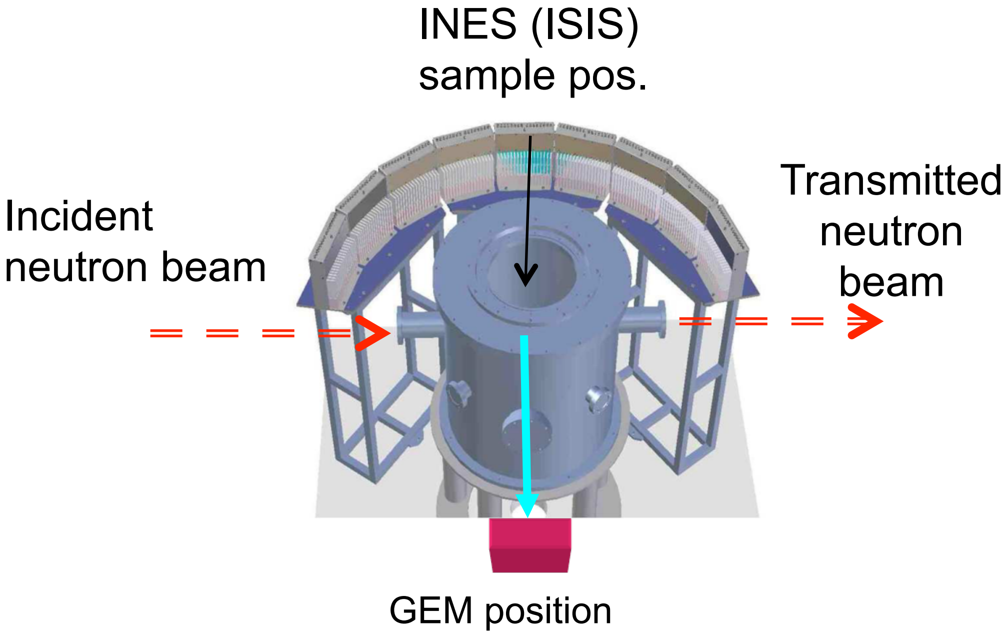
128 Pads of area 6x12 mm^2 have been used as anode

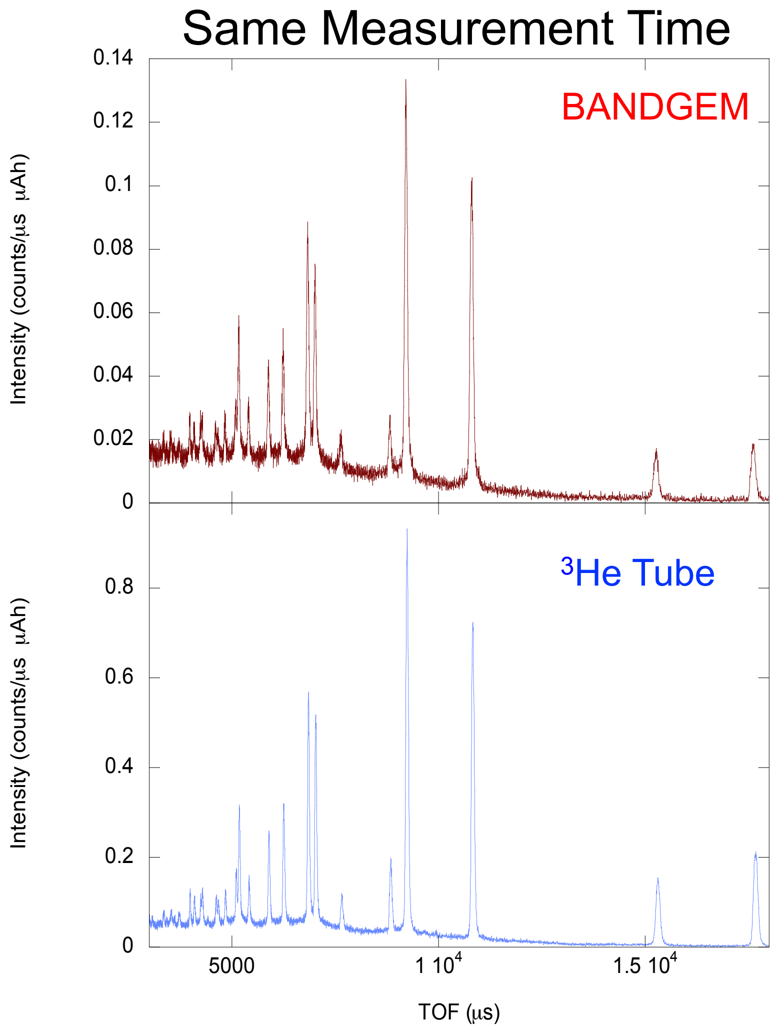
Lamella disposition on the pads



BANDGEM detector for neutron diffraction measurements

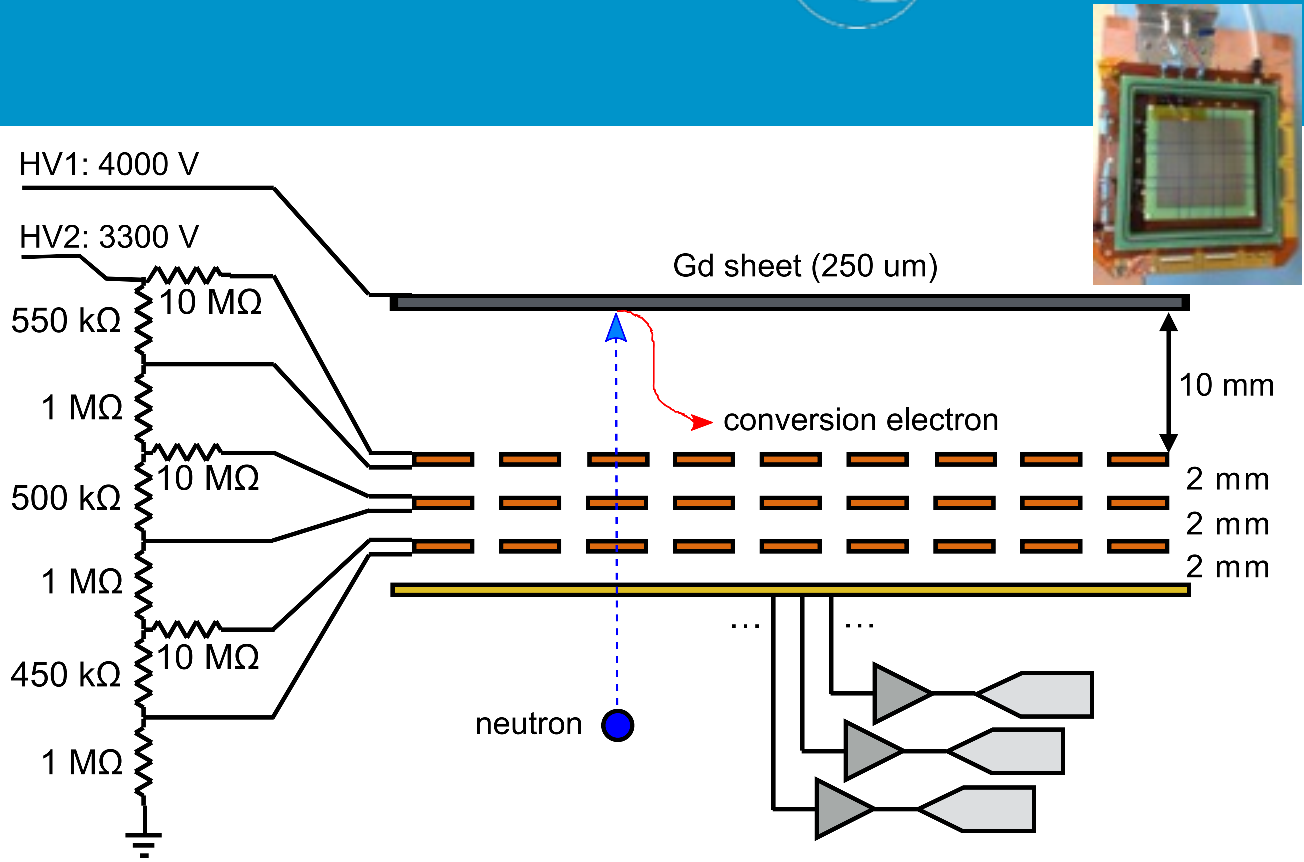
- First BANDGEM Prototype
- Bronze sample
- BANDGEM @ 90°
- ^{3}He counts about 3.4 times the BANDGEM
- BANDGEM/^{3}He Solid Angle Ratio = 0.45

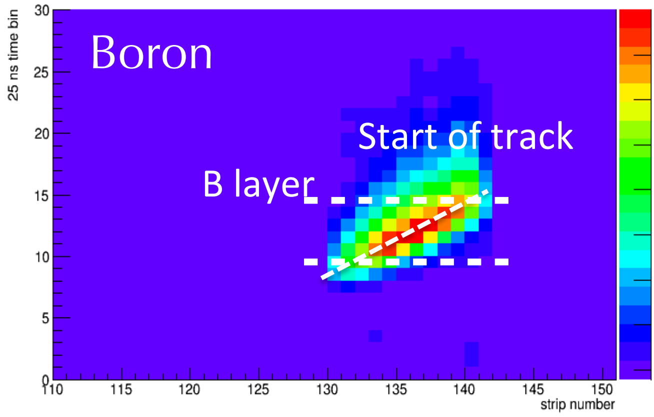




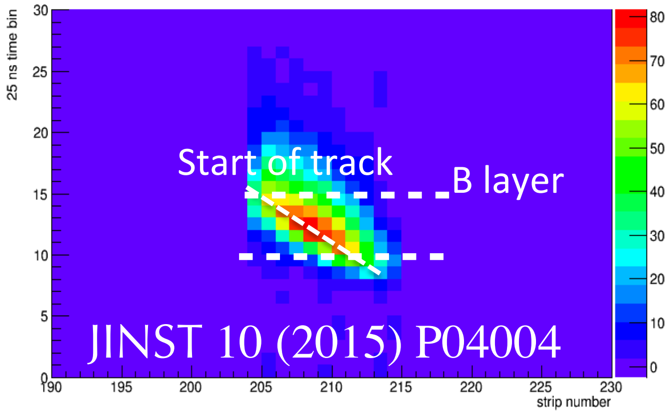
Gd-GEM

- NMX: <<1mm position resolution requirement, Time Resolved, ca. 1m^2 detector area
- Take Micro Time Projection Chamber concept from ATLAS experiment upgrade
- Resolution: use single layer Gd, look for electrons

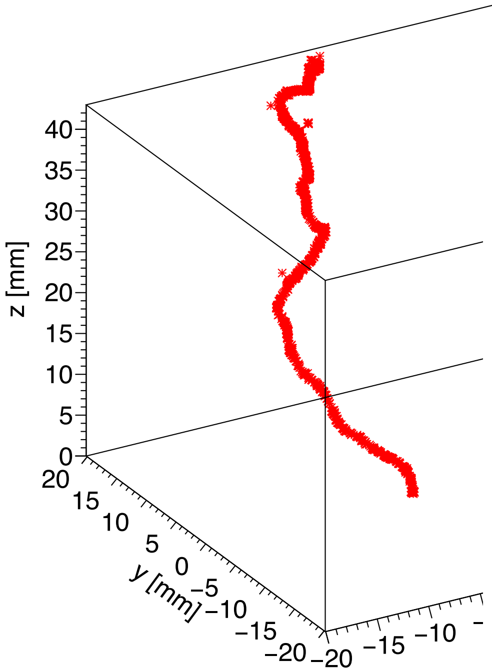


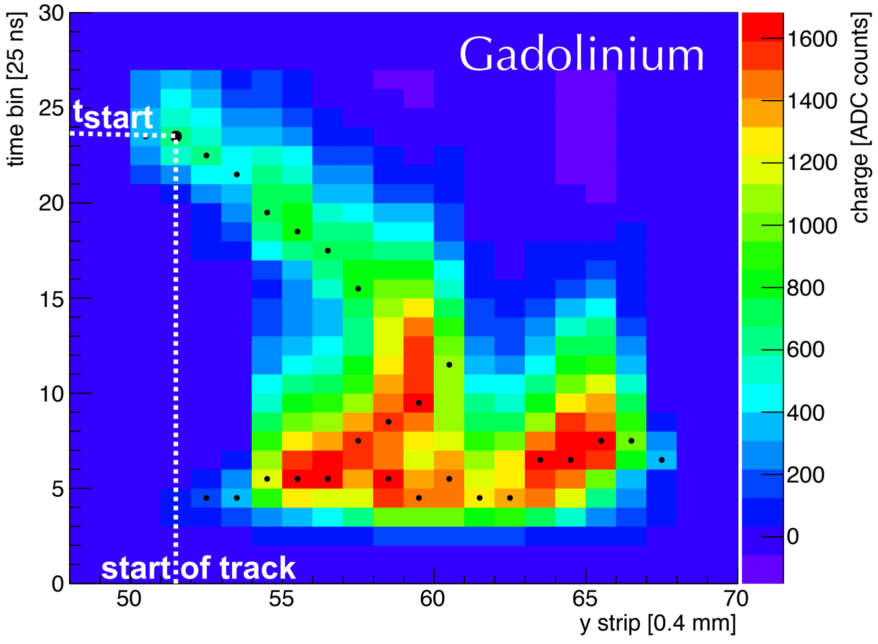


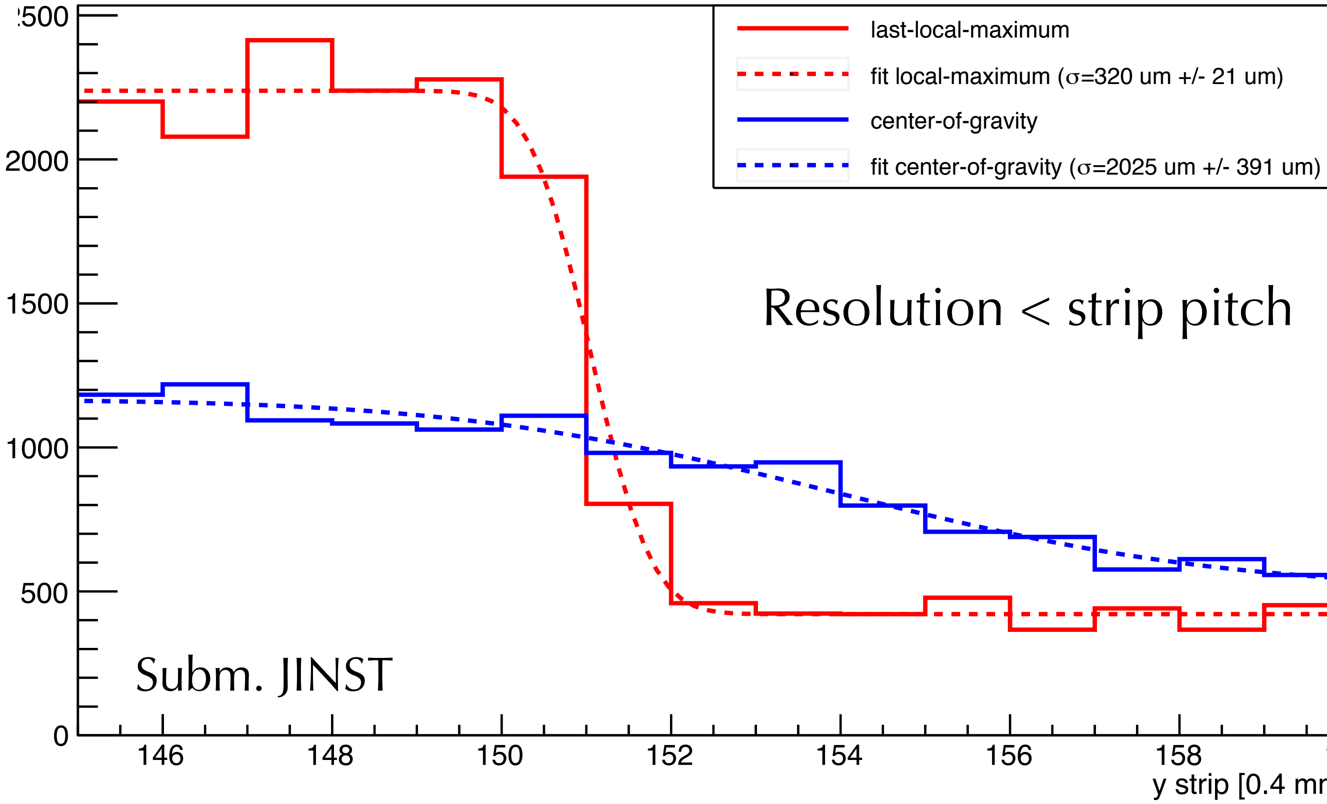
Track x



Track y







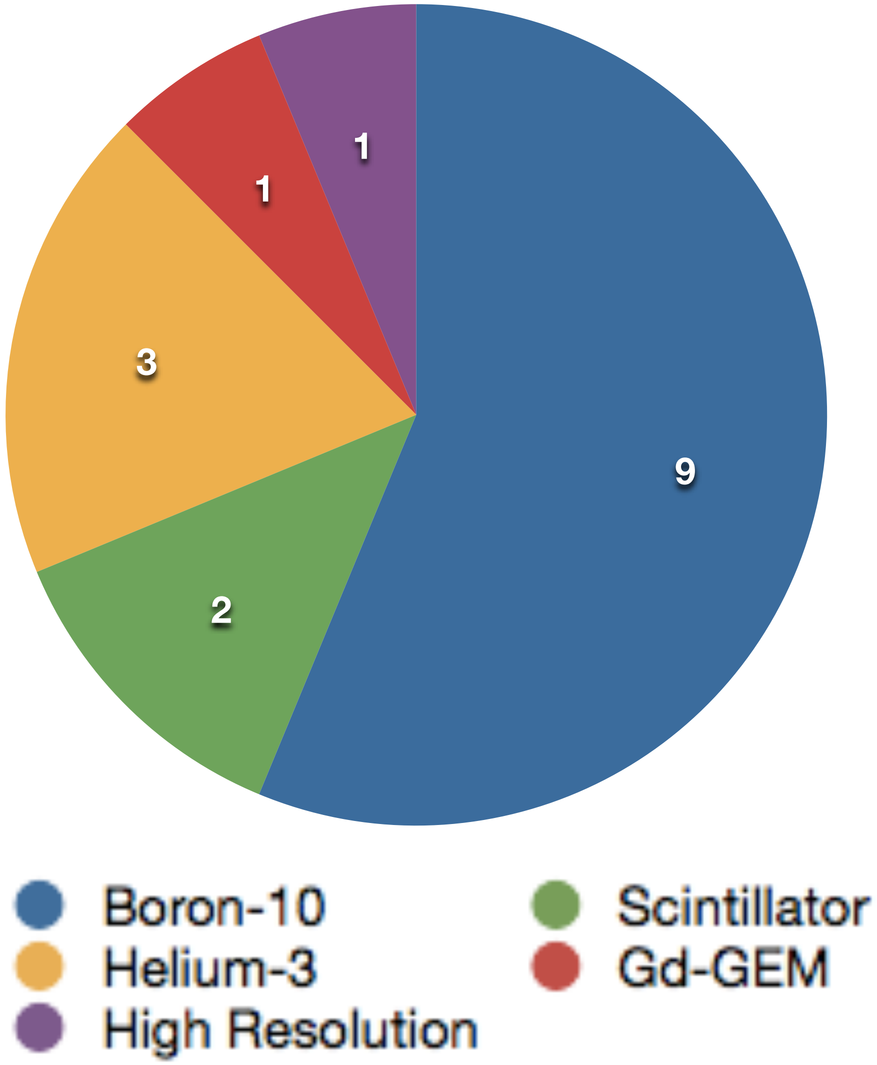
Preferred Detector Technologies for Baseline Suite

Instrument (class)	Technology	Preferred Design
ODIN (imaging)	Scint/Other	Neutron Camera/MCP
SKADI (SANS)	Scintillator	Pixellated Scintillator
LOKI (SANS)	10B-Based	BandGEM
FREIA (Reflectometry)	10B-Based	MultiBlade
ESTIA (Reflectometry)	10B-Based	MultiBlade
DREAMS (Diffraction)	10B-Based	Jalousie
BEER (Diffraction)	10B-Based	A1CLD/AmCLD
HEIMDAL (Diffraction)	Scintillator	WLS Fibre Scintillator
NMX (MX)	Gd-GEM	Gd-GEM
CSPEC (Dir. Spectroscopy)	10B-Based	MultiGrid
VOR (Dir. Spectroscopy)	10B-Based	MultiGrid
BIFROST (Spectroscopy)	Helium-3	?
IMAGIC (Diffraction)	10B-Based	Jalousie
VESPA (Spectroscopy)	Helium-3	Tubes?
MIRACLES (Spectroscopy)	Helium-3	Tubes?
TREX (Dir. Spectroscopy)	10B-Based	MultiGrid

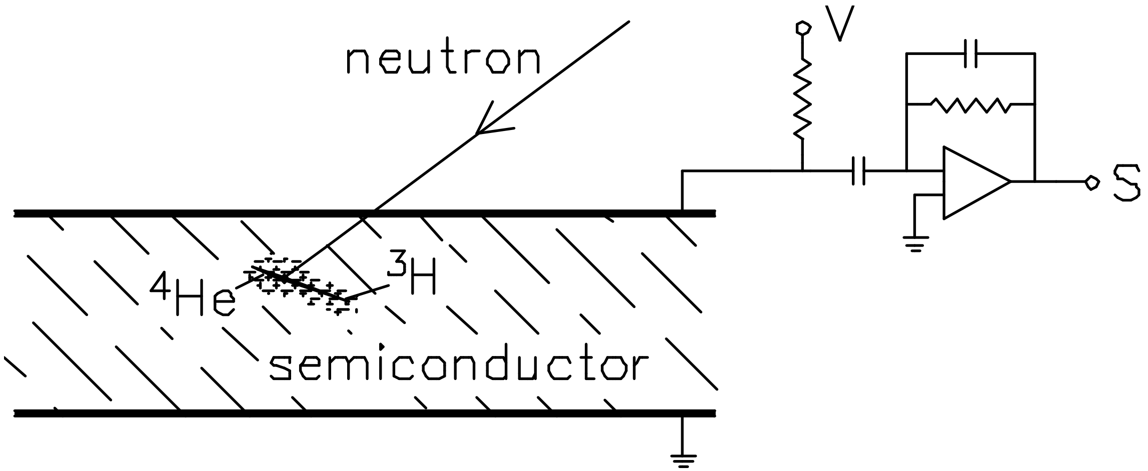
arXiv:1411.6194

Detectors for ESS will comprise many different technologies

Best-Guess at Detector Technologies for 16 Instruments:



Semiconductor Detectors



^{6}Li-loaded semiconductor

$$n + {}^6\mathrm{Li} \rightarrow {}^4\mathrm{He} + {}^3\mathrm{H} + 4.79\ \mathrm{MeV}$$

$$\sigma = 940 \frac{\lambda}{1.8} \mathrm{barns}$$

Semiconductor Detectors-cont'd

- ~1,500,000 holes and electrons produced per neutron (~2.4×10^{-13} coulomb).
  - The detector acts as a capacitor. The ionization partially discharges the capacitor and can be detected directly without further amplification.
  - However, standard device semiconductors do not contain enough neutron-absorbing nuclei to give reasonable neutron detection efficiency.

This is a challenge for future development.

Concluding remarks

Detectors must be chosen/DESIGNED for the specific application.

Requirements to be considered when designing detectors:

- Space/Time resolution
- Gamma-ray sensitivity
- Count rate
- Environment (B field, temperature etc)
- Digitize!

^{3}He replacement technologies and the large amount of new instrumentation is driving the detector development

First post-^{3}He developments are coming to realization

Detectors for future instruments are going to look rather different