**Gas detectors** where the charged particle released after the neutron capture ionize the gas and the electrons thus produced are collected by an electrode in ionization or proportional modes.

Single tubes can be used. Position Sensitive Tubes are used. A single resistive wire collects the charge and the charge separation at the tube ends is used to identify the neutron arrival position.

Two dimensional detectors often employed the multi-wire configuration. The GEM are also used with solid converters, this technology is not yet fully developed.

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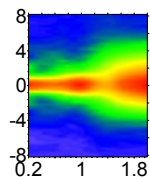
Scintillators where the energy is stored and released through a luminescence process. The light so produced can be detected using high sensitivity detectors (e.g. photomultipliers).

There are different good scintillators but there are different drawbacks mainly connected to the γ-ray sensitivity and to the best light collection. The most obvious light detector, e.g. the photomultiplier has a high cost, operates at high voltage and is sensible to magnetic fields.

A good scintillator (ZnS:Ag with ^{6}Li) is not much transparent. Other ^{6}Li containing scintillators exist (lithium glass) with a smaller light output. There exist also other less standard solutions like ^{10}B containing plastic scintillators or liquid scintillators.

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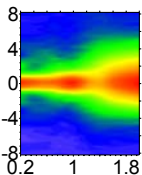
Solid state where a converter (normally outside the sensor) produces charged particles which are then detected. This technology is mature in many fields (particle trackers) but it is not yet widely used in the case of neutrons.

It offers good spatial resolution in 1-d and 2-d PSD but no many converters are adequate for neutron detection. Also the γ-ray sensitivity can be higher than in other cases.

This technology is becoming more interesting as the price is decreasing opening new configurations.

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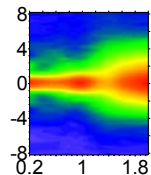
Imaging systems exist which are not able to detect single neutrons but only the neutron intensity (e.g. image plates). Alternatively imaging is possible using a scintillator coupled to a light detecting device, like CCD cameras of C-MOS sensors. These devices are adequate for rather good spatial resolution with thermal neutrons.

There is no possibility of single neutron detection and timing of the neutron arrival. Improvement of this technology (specially C-MOS) is expected in the near future.
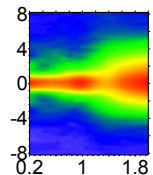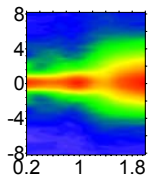
Special detectors. There exist detection devices appropriate for special applications. When rather high energy (in the MeV range) neutron must be detected the proton recoil can be employed. Appropriate ***polymers*** can be used using the scintillation capability. In this way it is possible to determine the neutron energy.

An alternative for high energy neutron detection and approximate energy spectrum measurement is the ***Bonner sphere***: a moderating material, like a hydrogen containing polymer, is used around some thermal neutron detectors.

To measure high neutron flux often a ***fission chamber*** is used. Based on a thin layer of fissile element (^{235}U, ^{239}Pu) and charge deposition in a gas. Minimum γ-ray sensitivity.
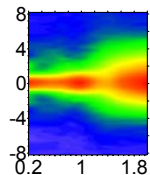
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Special detectors. There exist tests using the GEM (Gas Electron Multiplier) configuration. The GEM foils are coated with a (thin, 1-3 μm) ^{6}Li or ^{10}B converter. Several foils can be used in the same device.
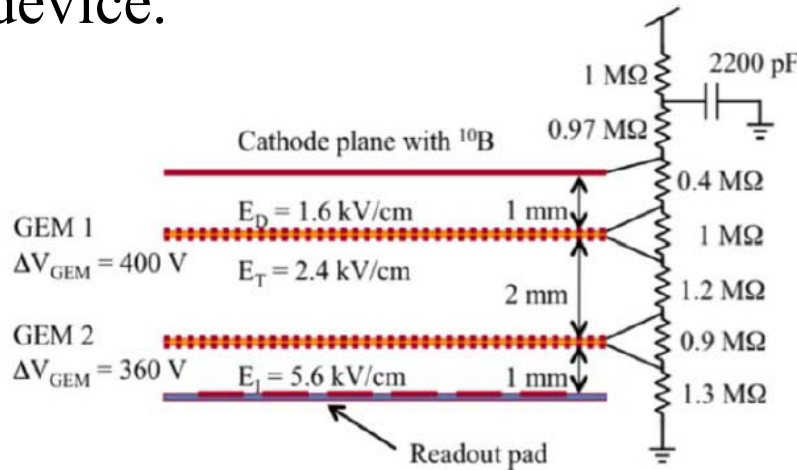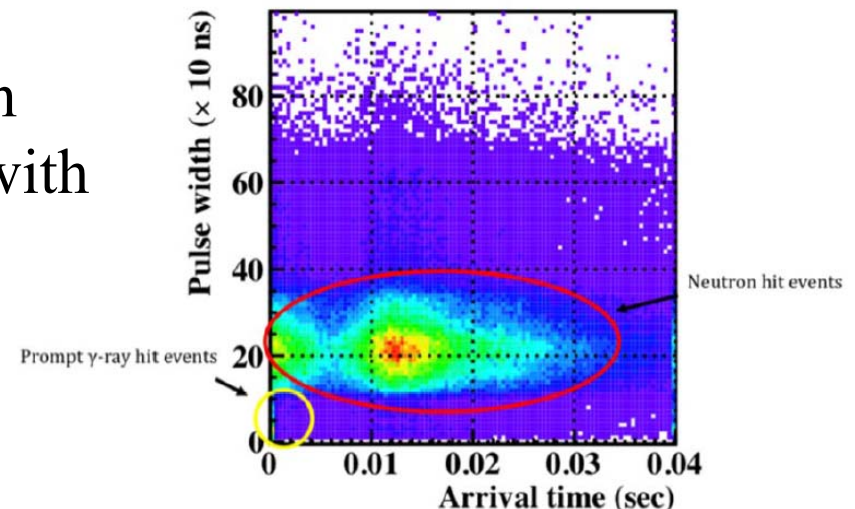
Schematics of a GEM neutron detector. KEK, Japan.

The converter for high energy neutron can be a hydrogenated material.

Cathode plane with ^{10}B

1 MΩ   2200 pF
0.97 MΩ

GEM 1
ΔV$_{GEM}$ = 400 V
E_D = 1.6 kV/cm   1 mm   0.4 MΩ
E_T = 2.4 kV/cm   1 MΩ
2 mm   1.2 MΩ

GEM 2
ΔV$_{GEM}$ = 360 V
E_I = 5.6 kV/cm   1 mm   0.9 MΩ

Readout pad   1.3 MΩ

Test of ToF Position Sensitive Detector with GEM

Pulse width ($\times$ 10 ns)

Neutron hit events

Prompt γ-ray hit events

Arrival time (sec)

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Major application of neutron detection (USA, 2008)

Oil and gas detectors   3 %

Neutron scattering and related techniques   10 %

Homeland security   87 %

Low energy neutrons are ideal particles for tests of Quantum Mechanics due to the reduced interaction with the environment. Specific detection devices can be necessary for these special experiments.

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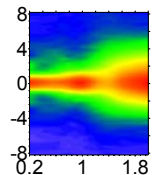
One of the most demanding application is the neutron scattering for condensed matter studies. The neutron energy range is fairly large:

from 1 meV up to 1 eV and more

The neutron scattering in this case is an intrinsically ***intensity limited technique***.

As many neutrons as possible must be detected is this sort of experiments because the sources are weak.

The intrinsic γ-ray background must be reduced as much as possible because it is normally rather high. A typical γ-ray efficiency smaller than 10^{-6} (10^{-8} is often required) in the MeV range must be obtained.

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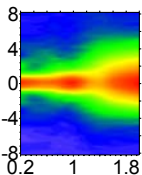
Required performance when a single neutron has to be detected

a) Detection efficiency E = 0.1 meV – 100 meV ~ 1 (>0.7)

b) Detection efficiency for γ-ray E = 0.01 MeV – 10 MeV < 10^{-6}

c) Pixel size ranges from 0.1 x 0.1 mm² to 3 x 3 cm²

d) Counting rate 1 MHz local and global

e) Dimension up a 50 m² (ideal cost ~ 200-500 k€/m²)

f) Flexibility in terms of shape and organization, installation under vacuum and magnetic filed, good long term stability, <0.1 % over a week at least

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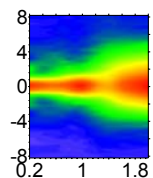
The best reaction for this application is:

$$^3\text{He} + \text{n} = {^3\text{H}} + \text{p} + 0.77 \text{ MeV}$$
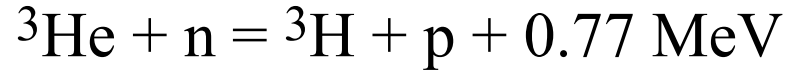
This reaction can be properly applied in gas detector systems. The γ-ray efficiency is intrinsically low because the low atomic number of ^3He. The DQE is unity and the detection efficiency can be made high by using a pressurized gas to increase the density.

In a gas the ionization charge is about 6 fC, which can be increased in the proportional regime. Often one can collect 1 pC or more.

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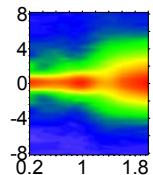
Schematics valid for all gas detectors. Typical application with ^{3}He and ^{10}BF$_3$ converters.

R_L

+V   -V$_{ref}$

Gas container, normally stainless steel. Total pressure up to 20 bar
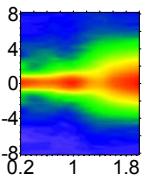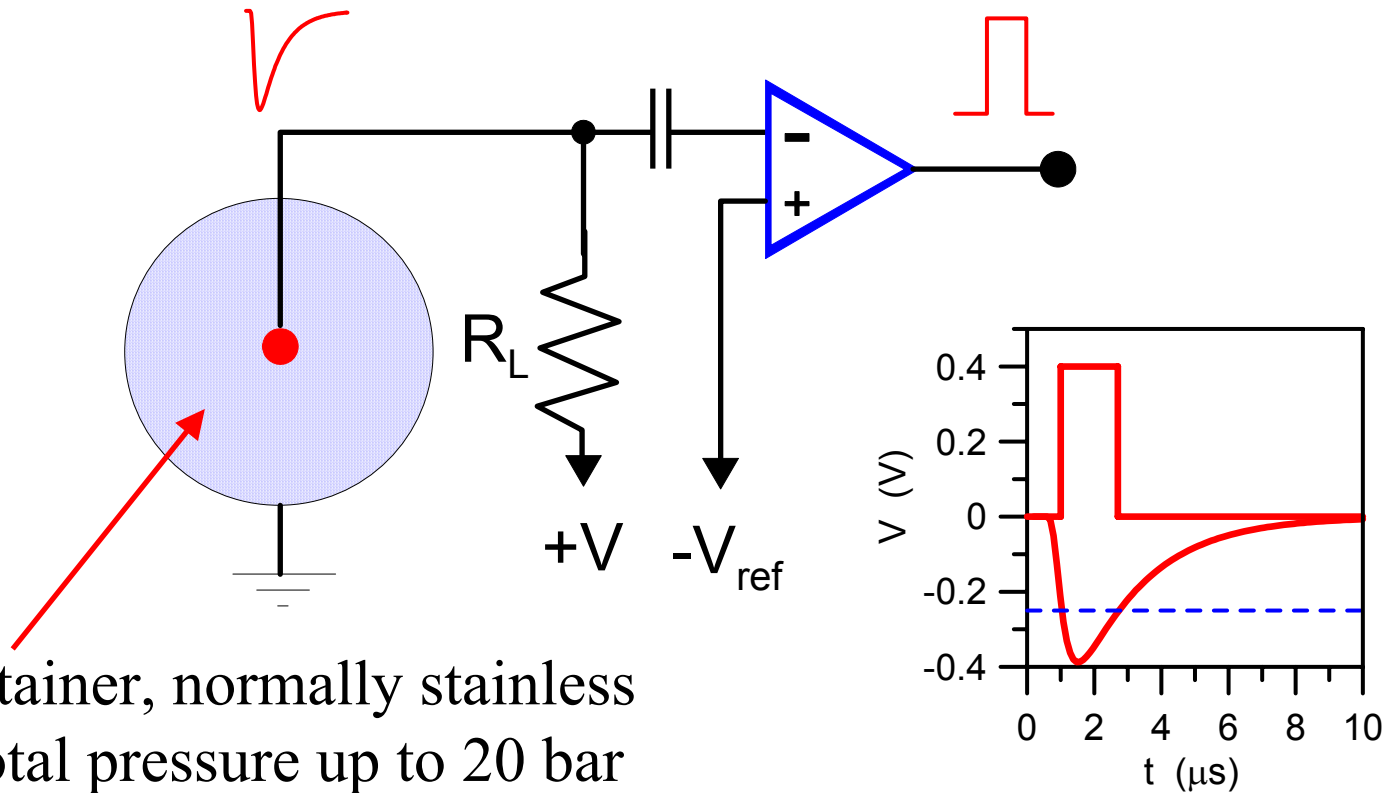
Large area detector (vertical tubes on the left of the picture, 3 m long, 3 cmm diameter, 6 bar) at the Institut Laue Lagevin (Grenoble, France), inside a vacuum chamber. A separation is needed between the vacuum chamber and the HV connectors.

Small ^{3}He tubes up to 20 bar. Notice the squashed tube having a more uniform efficiency in the transverse direction. Much worse electric field distribution.
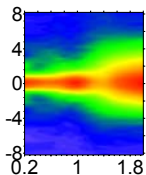
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To determine the capture position in long tubes a resistive wire is used. The encoding can be either resistive or based on the rise time. In this way it is possible to use sealed individual tubes, a system more efficient than a multi-wire chamber which cannot be easily employed at high gas pressure.
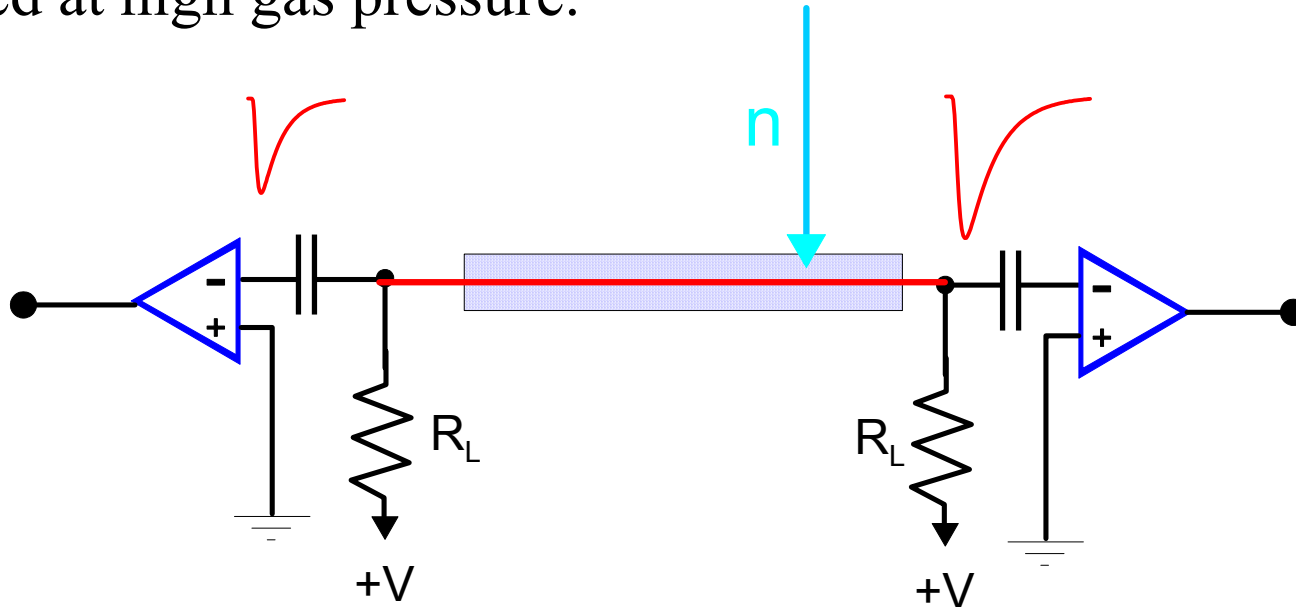

Tubes 1 m long with a diameter down to 0.7 cm have been used.
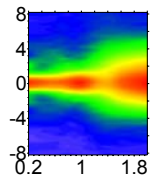
Although the ^{3}He technology has good performances and is well assessed there are limitations in terms of spatial resolution and velocity. The charge collection time results in a typical **pulse length of** 2-5 µs. In addition the gas tubes cannot be easily operated under vacuum. Proper systems which maintain the **high voltage** (1-2 kV) connection in air while the sensible part is under vacuum must be employed. **High magnetic fields** can represent an additional problem.

An alternative can be a similar tube using ^{10}BF$_3$ as gas converter. Because of the toxicity of this gas, these tubes are limited to **atmospheric pressure** and cannot be operated under vacuum.
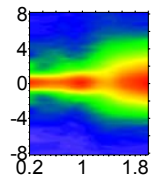
The ^{3}He Crisis

Report from USA

One major obstacle to the widespread use of neutron detectors in RPMs has been a global shortage of helium-3 (^{3}He), an extremely rare isotope of helium.

In order to protect the nation from a possible nuclear attack, the Department of Homeland Security (DHS) has placed radiation portal monitor systems at US ports of entry to detect illicit nuclear materials.

Size of the Helium-3 Stockpile, 1990-2010
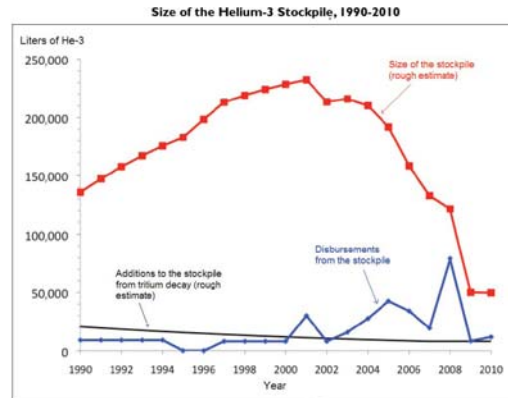
Source: Adapted from Steve Fetter, Office of Science and Technology Policy, "Overview of Helium-3 Supply and Demand," presentation at the American Association for the Advancement of Science Workshop on Helium-3, April 6, 2010.

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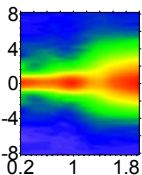
In the future much more control will be applied:

Pedestrian radiation portal monitoring
Air freight radiation portal monitoring
Crane based radiation portal monitoring
Air luggage radiation portal monitoring
Railway radiation portal monitoring

The crisis is complex and largely due to the stop of the production of ^{3}H used in nuclear weapons. The ^{3}He is just a byproduct of these weapons. The production might start again in USA to face the urgent need for additional, large scale neutron detectors for homeland security.
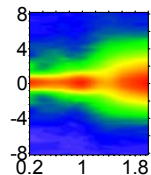
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The no ^{3}He detectors, *scintillators*

The already widely solution is based on scintillators. The lithium glass is the best one. The efficiency can be made high. The γ-ray efficiency is low but worse than ^{3}He. Improvements are possible using pulse shape analysis (to be developed, possible using modern technology). HV necessary if photomultipliers are employed, problems with vacuum. New devices, e.g. SiPM might be used. No operation close to magnetic fields.
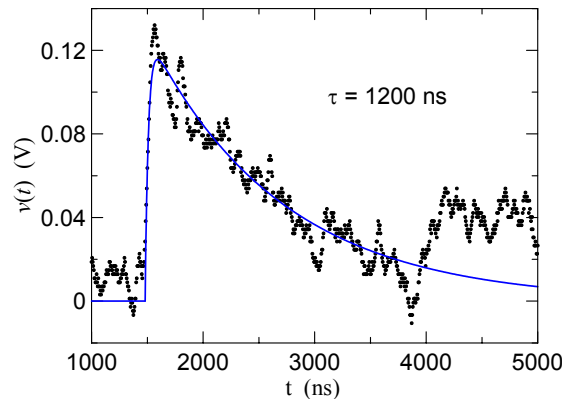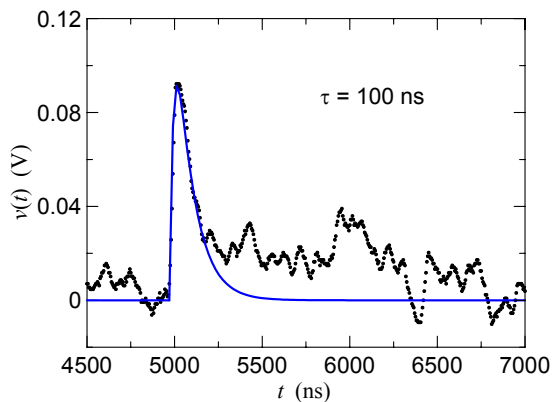
SiPM pulse, GS20, ZnS:Ag+^{6}Li
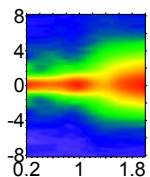
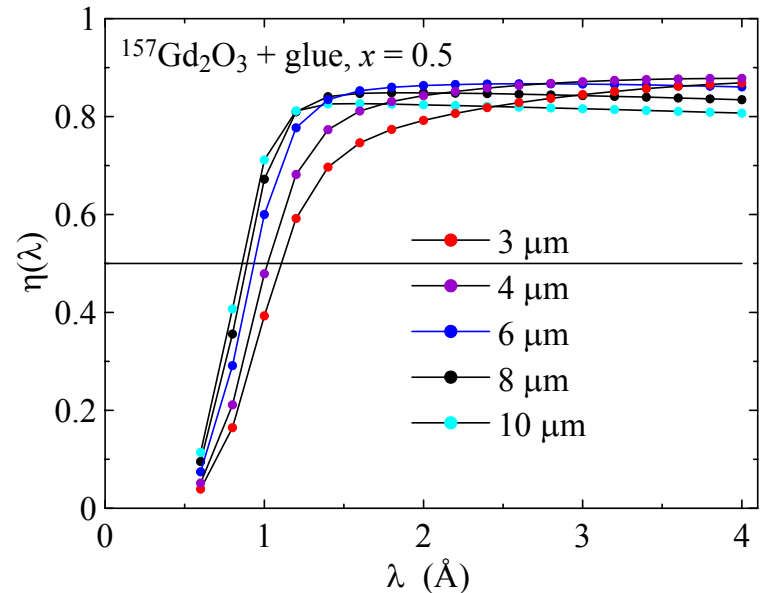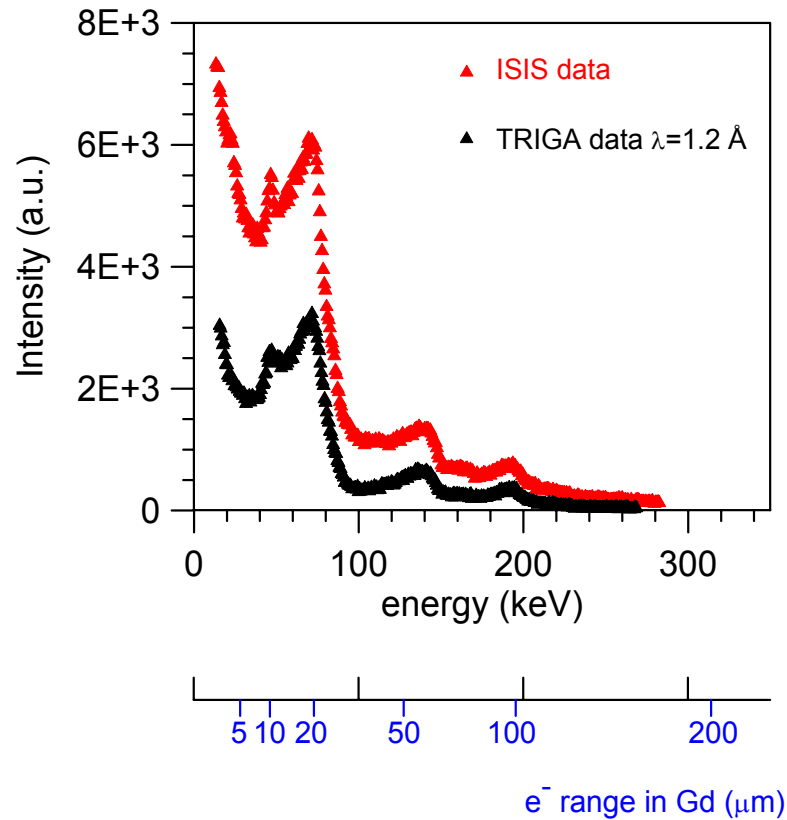The no ^{3}He detectors, *solid state devices*, still in their infancy.

SiPM are still too noisy. They are flexible, operation in magnetic field, no HV, operation in vacuum. Lithium glass still too expensive. Residual radioactivity too high. More work to be done on pulse shape analysis.

PIN diodes are good when coupled to a proper converter like ^{157}Gd which is efficient up to rather low energy (less than 0.1 eV). Operation in magnetic field and in vacuum. Easy coupling to integrated front-end electronics. Neutron signal fairly small (down to 1 fC).
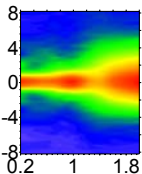
Si microstrips, performance similar to the PIN diode. Useful for high spatial resolution and rather fast response.
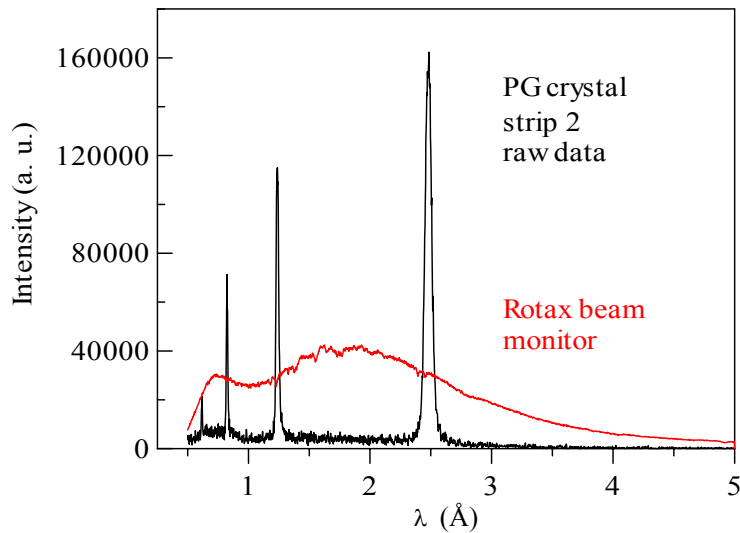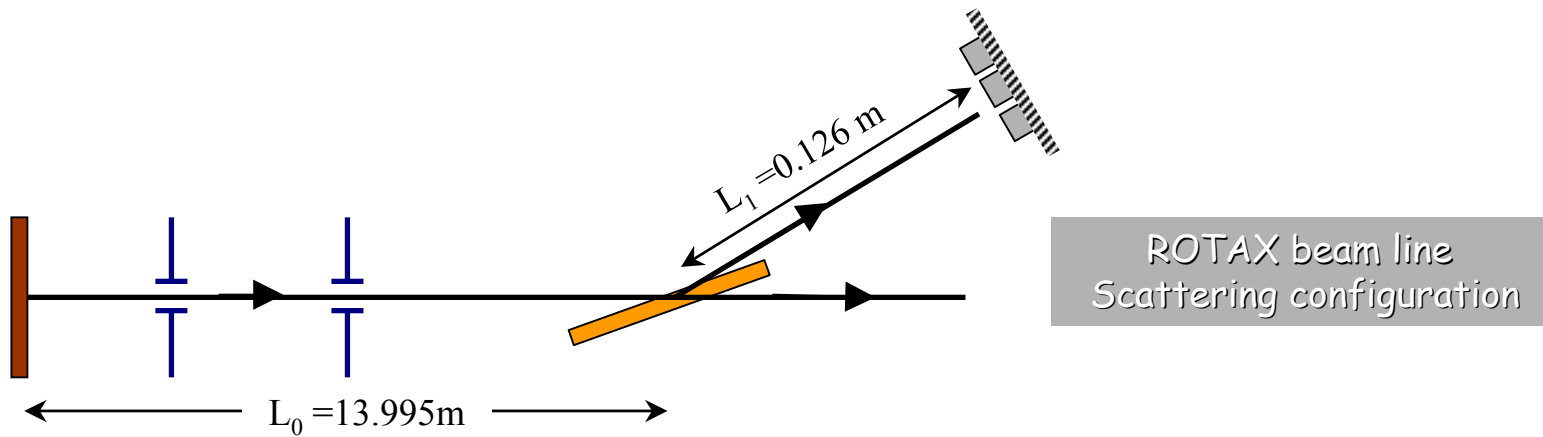
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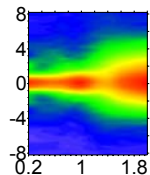
Secondary electron energy deposition in Gd after neutron capture measure with a PIN coupled to a slow (1 μs) VA preamplifiers

Intensity (a.u.) vs energy (keV)
- ▲ ISIS data
- ▲ TRIGA data λ=1.2 Å

e⁻ range in Gd (μm): 5 10 20 50 100 200

$^{157}Gd_2O_3$ + glue, $x = 0.5$

$\eta(\lambda)$ vs λ (Å)
- ● 3 μm
- ● 4 μm
- ● 6 μm
- ● 8 μm
- ● 10 μm

Simulated neutron detection efficiency of two PIN diodes coupled to an isotopic ^{157}Gd converter (6 €/mg).

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ROTAX beam line
Scattering configuration

$L_1 = 0.126$ m

$L_0 = 13.995$ m

PG crystal
strip 2
raw data

Rotax beam
monitor

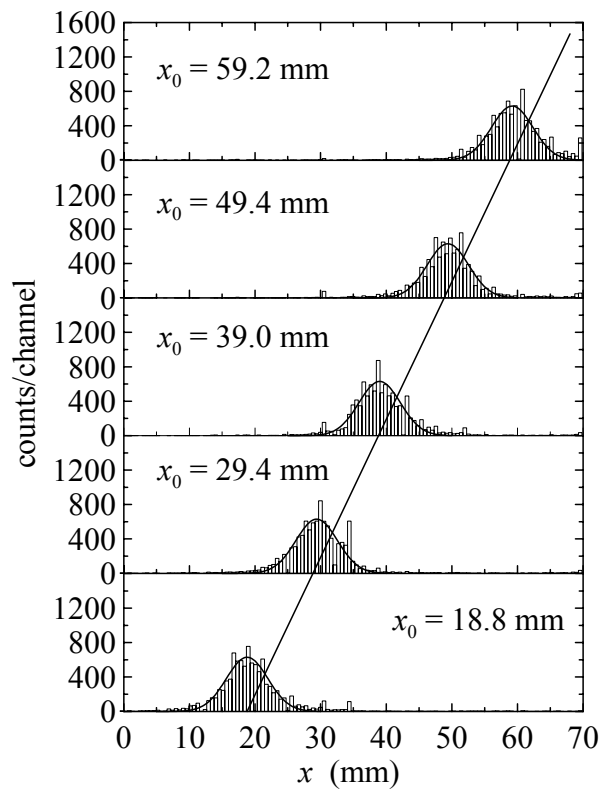Intensity (a. u.)

λ (Å)

ToF measurement of the neutron spectrum using a Si microstrip (40x70 mm^2, 0.5 mm effective pitch) coupled to a single natural thick Gd plate on the backplane.

The performance, after the ^{3}He crisis seems adequate in many applications.

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$x_0 = 59.2$ mm

$x_0 = 49.4$ mm

$x_0 = 39.0$ mm
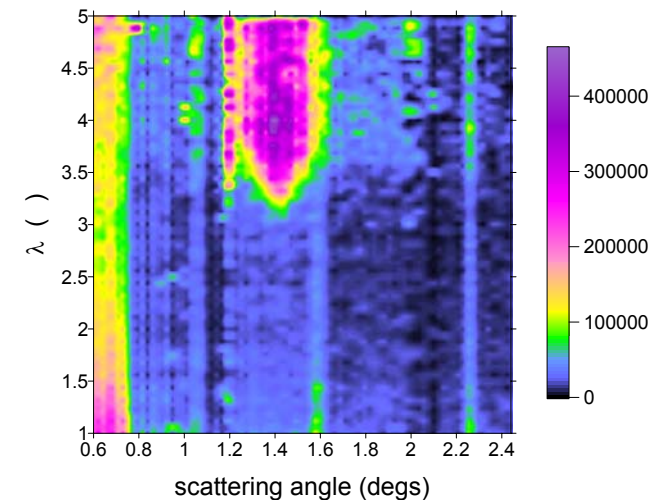
$x_0 = 29.4$ mm

$x_0 = 18.8$ mm
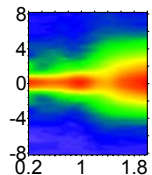
Si microstrip 1d detector, position determination with a ^{90}Sr source. Compact system with medium density front-end.
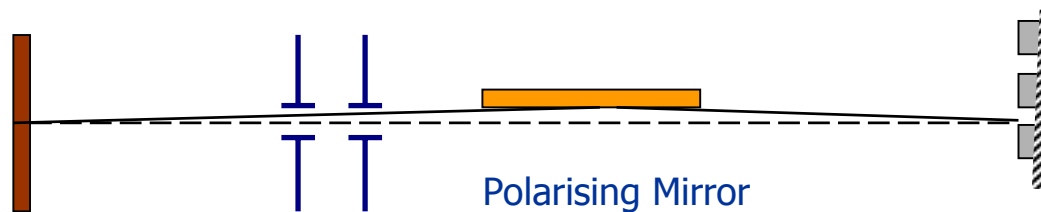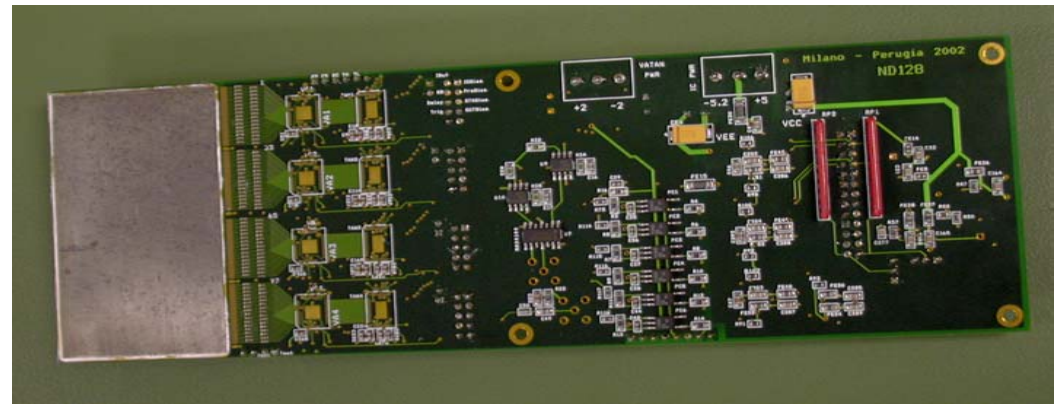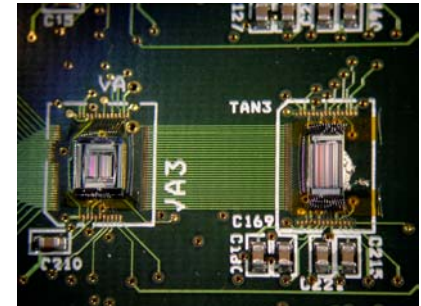
Neutron reflection at grazing angle.

Polarising Mirror

scattering angle (degs)

λ ( )

The no ^{3}He detectors, ***back to future***, the ^{10}BF$_3$ detectors.

Many tests have been performed to test old style ^{10}BF$_3$ gas detectors.

In applications like homeland security there is some chance but this is not the case for more demanding applications in terms of life time for instance. The general performance is definitively worse than the ^{3}He detectors.
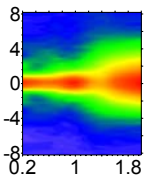
Catania Novembre 2014
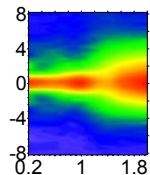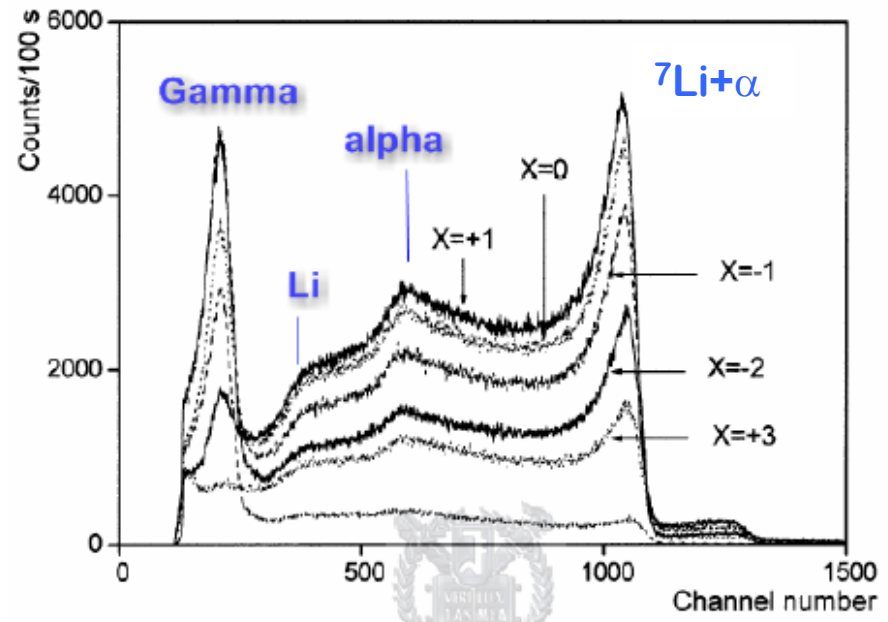
The no ^{3}He detectors, *solid ^{10}B converters*

Some prototype has been produced based on a gas chamber (argon+stopping gas) where several thin (1 mm) Al sheets coated (3 μm thick) with ^{10}B$_4$C are properly inserted. This approach is similar to that used in the case of GEM.

Al substrate

10B   10B

n

gas volume
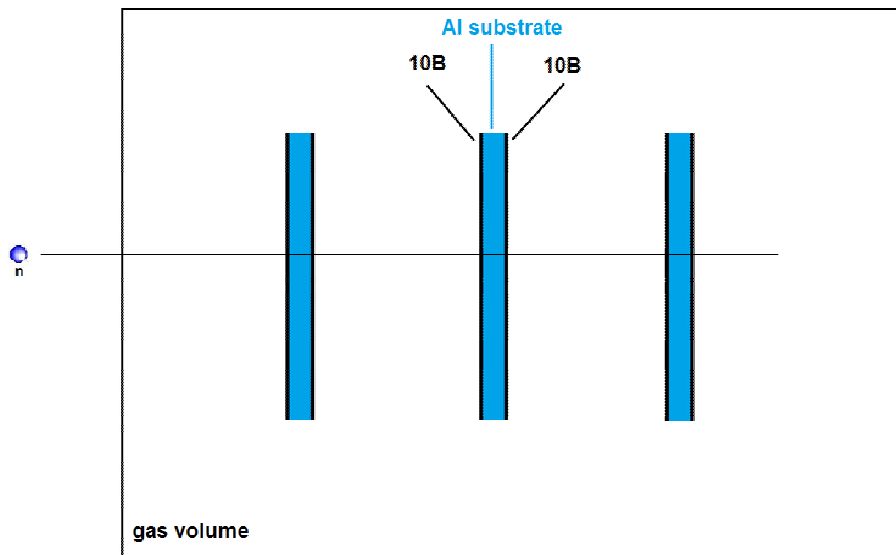
Schematics of the (perpendicular) neutron capture.

This is a collaboration between the Institut Laue Langevin (Grenoble) and the European Spallation Source (Lund). The system provides a 2 cm spatial resolution but it is fairly complex with a detection efficiency lower than 60%.
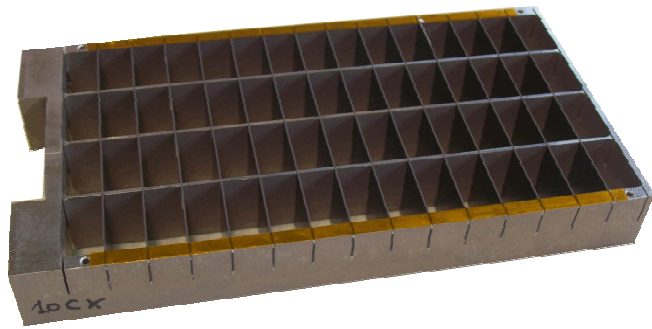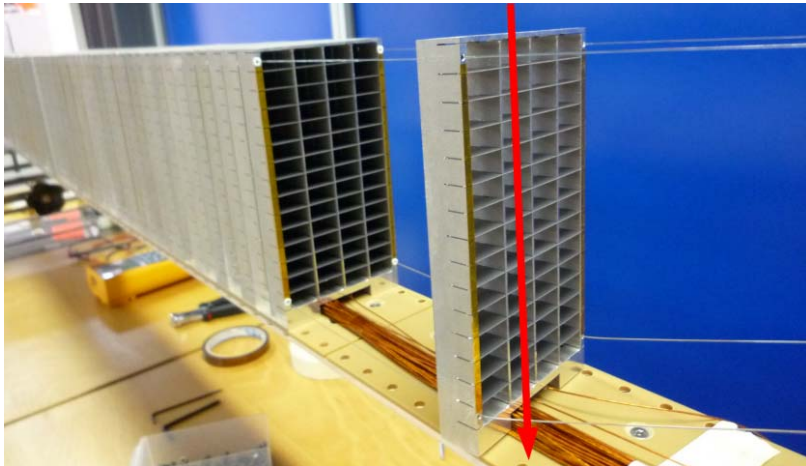
More effort is necessary to get a good enough performance.
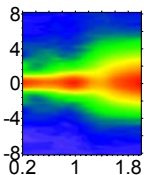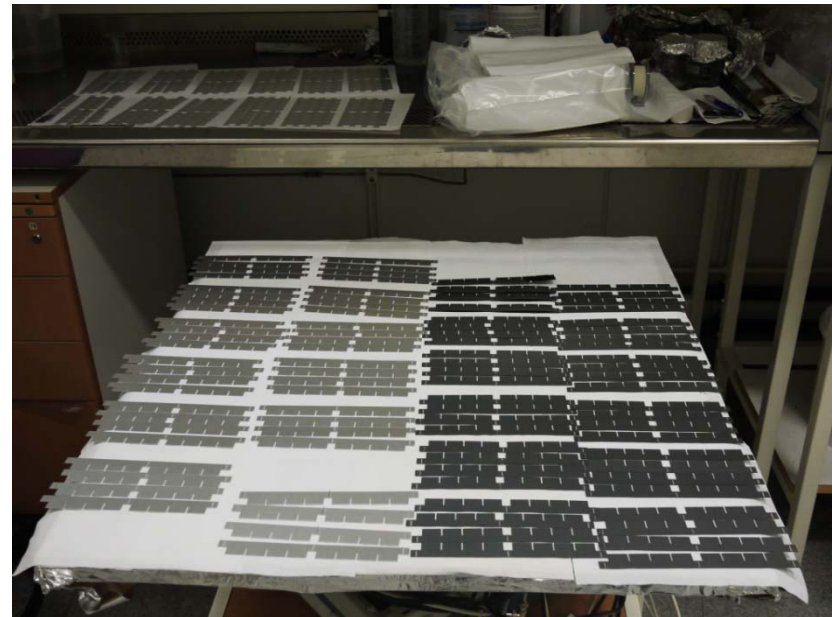
Future developments, some examples

The compound ^{10}BN is a semiconductor. The pyrolitic crystal (hexagonal) has been tested as neutron detector. This detector is based on a thin (1 mm) BN plate where a proper voltage (500 V) is applied. No much work has been done and the present performance is poor.

The BN has a high cost (100-200 €/cm^2) and the noise level is still high. No information about the γ-ray efficiency is available.

The scintillator Ce:^{6}LiCaAlF$_6$ (LiCAF) emits at 270 nm. It can be employed using a proper wavelength shifter, it seems promising in terms of the γ-ray discrimination. It seems possible to detected the emitted light using a wavelength shifter coupled to an APD.

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