Principle and fabrication of thermal neutron detectors

Bruno Guérard

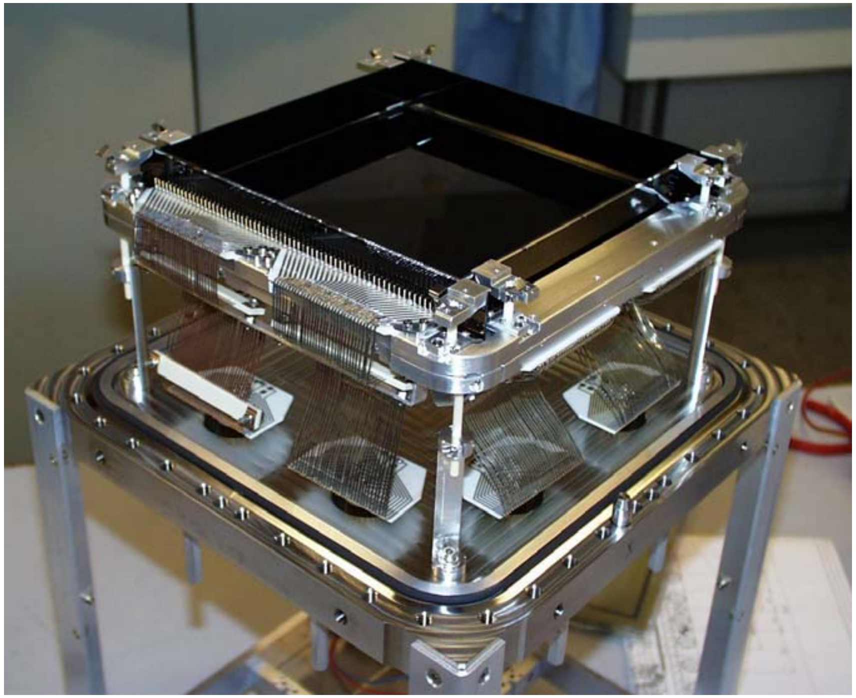
- Main detection parameters
- Light and charge readout detectors
- Some examples
- Development prospects

- How does one “detect” a neutron?
  - Can’t directly detect slow neutrons (neutrons relevant to materials science) - 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
- Then one can use some of the many types of charged particle detectors
  - **Gas proportional counters and ionization chambers**
  - **Scintillation detectors**
  - Semiconductor detectors
  - Image plate detectors
- Neutron instruments cover a broad range of applications. Each detector is almost unique in its design.

From large area, low resolution …

… to small area, high resolution

The 30 m^2 detector of the IN5 Energy spectrometer at the ILL



The MSGC developed for the D19 Single Crystal Diffractometer

Main parameters to consider in the design of neutron detectors

- Neutron detection efficiency
- Uniformity
- Localization accuracy
    - FWHM: Ability to separate 2 diffraction signals
    - Accuracy to determine the centroid of a diffraction signal
    - Position linearity
- Gamma sensitivity
- Time resolution
- Counting rate capability (local, global)
- Counting stability over time
- Other parameters: Cost, reliability, technique availability

Why high efficiency detectors are needed ?

Neutron detection efficiency ε : *Probability to localize a neutron crossing the sensitive area of the detector.*

Neutron beams produced by spallation sources and reactors for neutron instrumentation are several orders of magnitude lower in intensity compared to X-Ray beams delivered by Synchrotron sources.

Neutrons are also less interacting with matter than X-Rays, and the probability of interaction is strongly specific to the Isotope

→ Material samples must have a sufficient volume to produce enough measurement statistics in a reasonable time

→ Detection efficiency required >= 80% for thermal neutrons (1.8 Å)

Common nuclear Reactions for Neutron Detectors

- $n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 0.764$ MeV ($\sigma_c = 5330$ barns for 1.8 Å)
- $n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.79$ MeV ($\sigma_c = 937$ barns for 1.8 Å)
- $n + {}^{10}B \rightarrow {}^{7}Li^{*} + {}^{4}He \rightarrow {}^{7}Li + {}^{4}He + 2.31$ MeV+ gamma (0.48 MeV) (93%)
  $\rightarrow {}^{7}Li + {}^{4}He + 2.79$ MeV (7%)

  ($\sigma_c = 3840$ barns for 1.8 Å)
- $n + {}^{14}N \rightarrow {}^{14}C + {}^{1}H + 0.626$ MeV
- $n + {}^{157}Gd \rightarrow Gd^{*} \rightarrow$ gamma-ray spectrum + conversion electron spectrum (~70 keV)
- $n + {}^{235}U \rightarrow$ xn + fission fragments + ~160 MeV ($\langle x \rangle \sim 2.5$)

Natural fraction

${}^{10}B$: 19.8%

${}^{6}Li$: 7.6%

${}^{157}Gd$: 15,7%

Scintillators

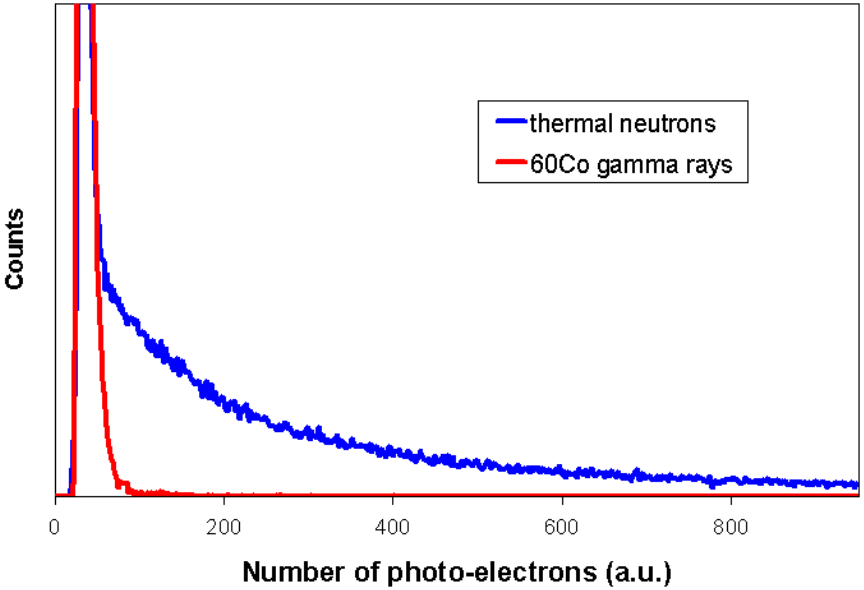
$$n + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{H} + 4.79\ \mathrm{MeV}$$

	GS20 glass (LiO_2)	**LiF-ZnS(Ag)**
Neutron detector efficiency	**transparent**	**~20% at 1 A**
Gamma sensitivity / 60Co	**10^{-3} when fibre coded**	**10^{-7} when fibre coded**
Speed	**70 ns decay constant**	**200 ns primary** **80µs afterglow**
Position resolution	**6,000 photons**	**150,000 photons**
Neutron count rate stability	**Good Pulse Height Resolution**	**No Pulse Height Resolution**

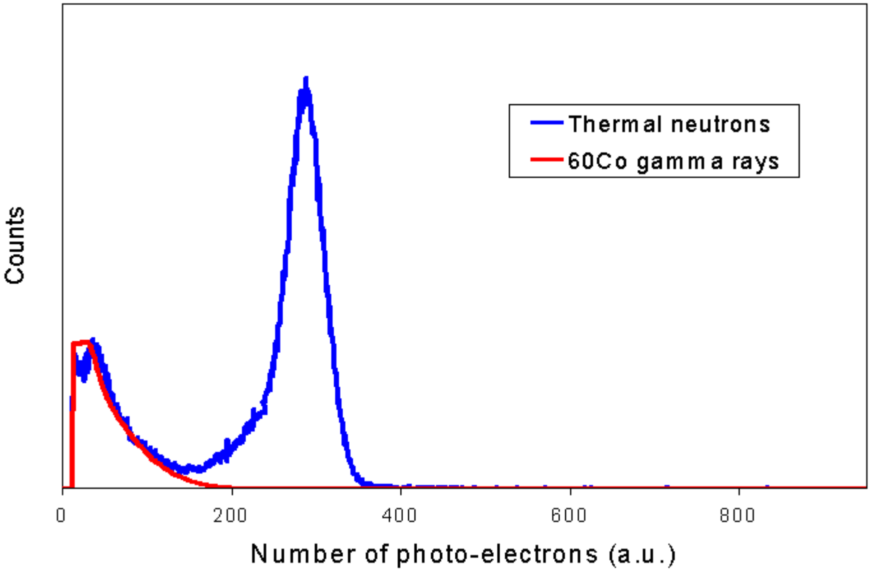
$$\sigma = 940 \frac{\lambda}{1.8}\,\mathrm{barns}$$

Broadly used at ISIS, SNS and JSNS
Difficult compromise between the number of photons, and the dead time.
→in spatial resolution OR in count rate

Light yield measurement



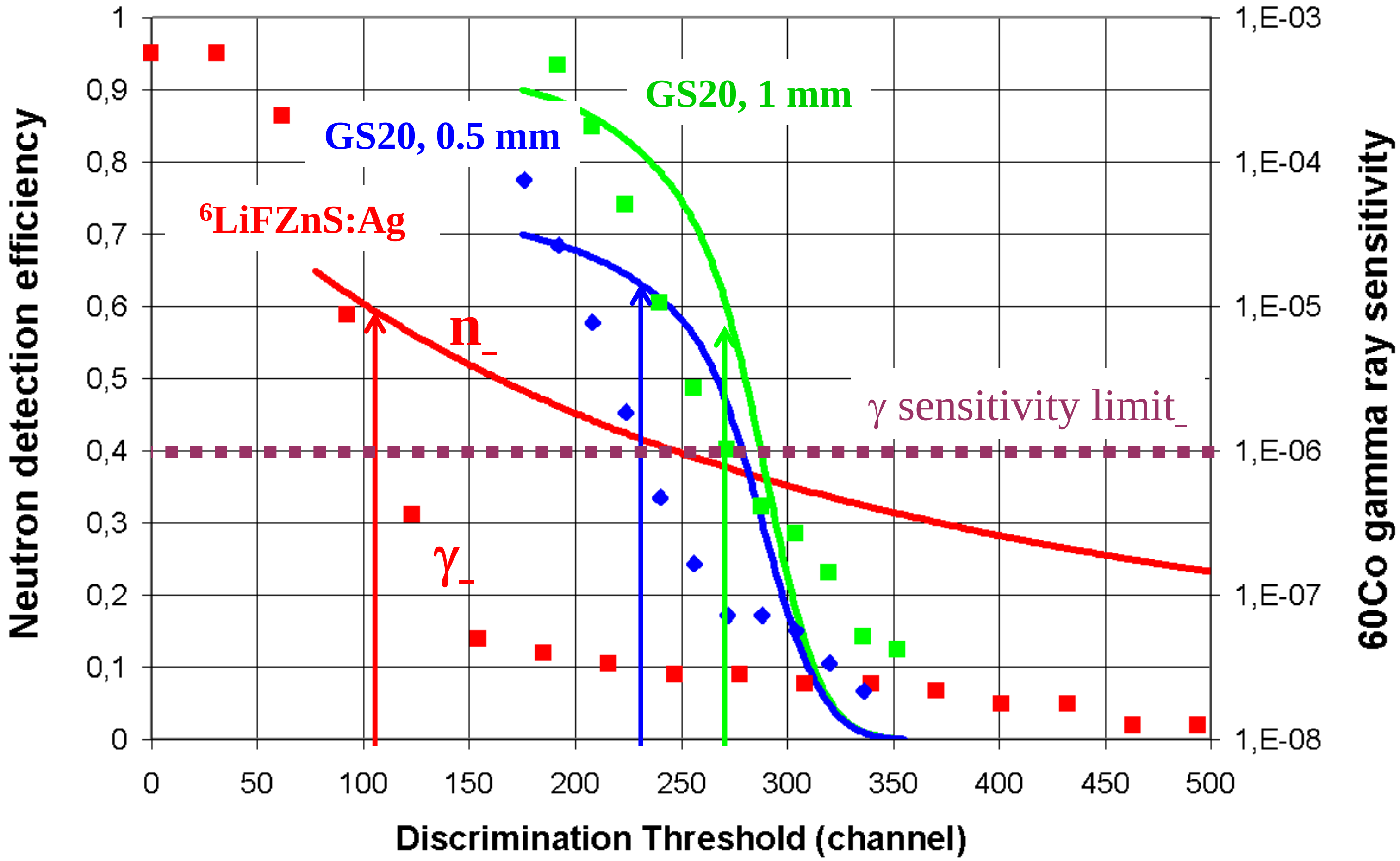
6LiF/ZnS:Ag scintillator_



0.5mm thick GS20 scintillator._

Scintillators in direct contact with a Position Sensitive Photomultiplier RS2486

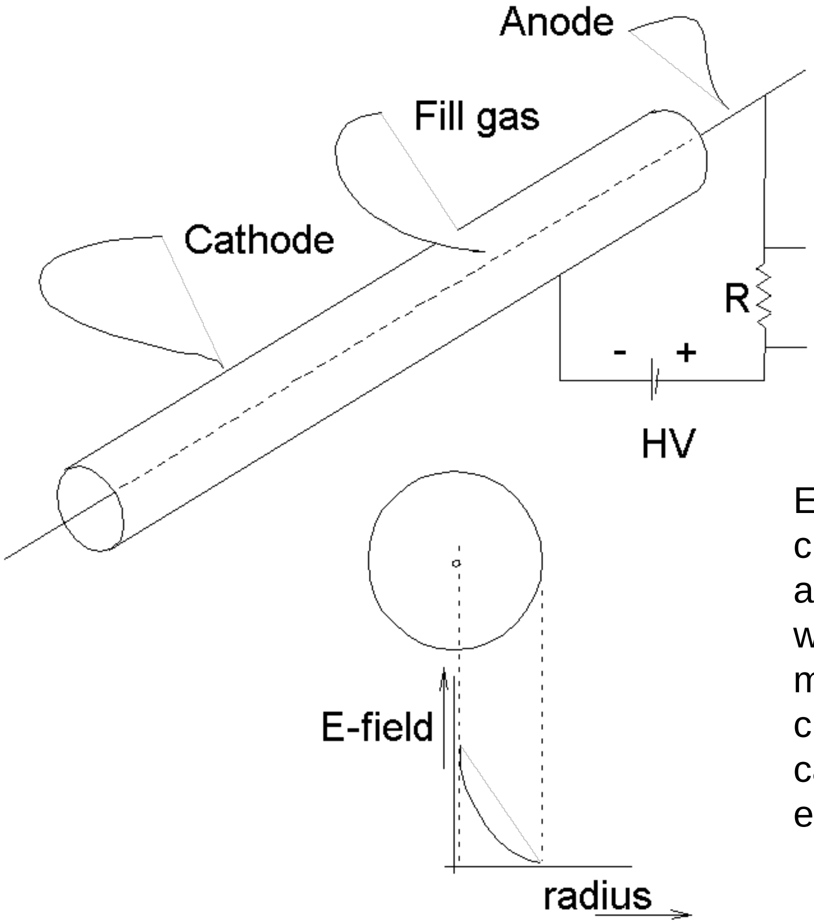
γ sensitivity and neutron detection efficiency (λ=1.8 Å)_



Scintillators in direct contact with a Position Sensitive Photomultiplier RS2486

Gas Detectors

Gas Proportional Counter



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

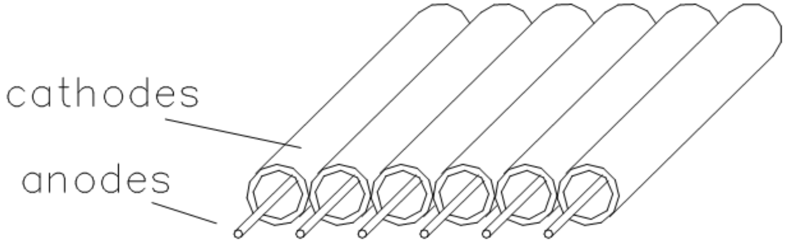
$$\sigma = 5333 \frac{\lambda}{18} \quad barns$$

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

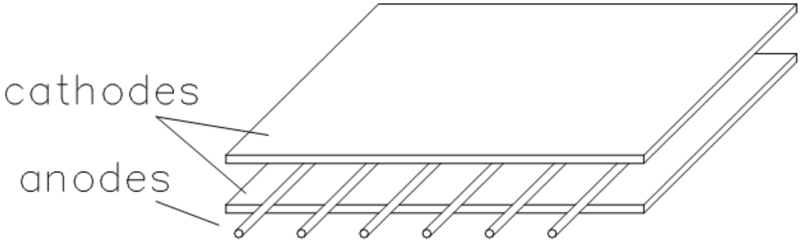
Electrons **drift** toward the central anode wire. When they get close, they accelerate sufficiently between collisions with gas atoms to ionize the next atom. A ***Townsend avalanche*** occurs in which the number of electrons (and ions) increases the number many-fold, about x10^{3}. Separation of these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

Gas Detectors

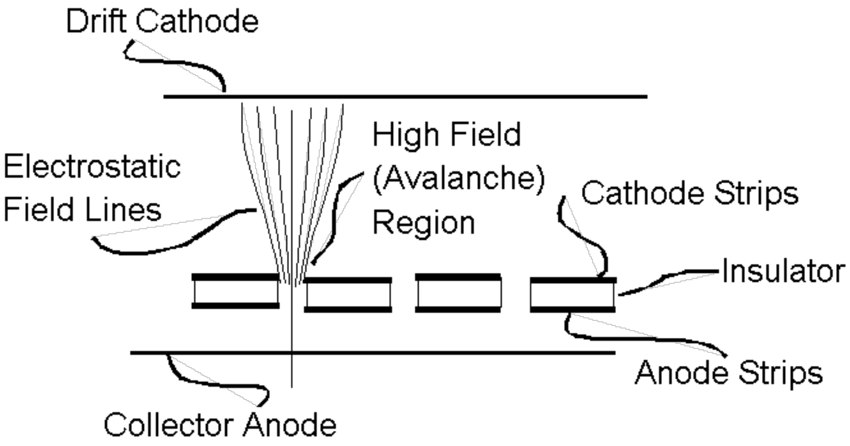
Individual counters



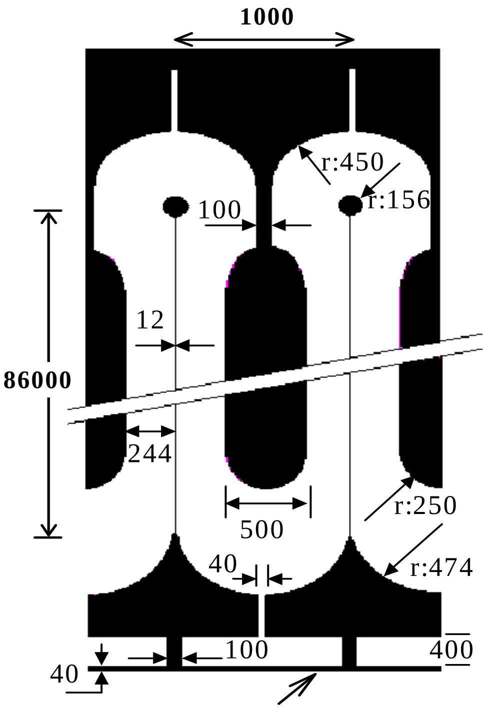
MWPC



GEM



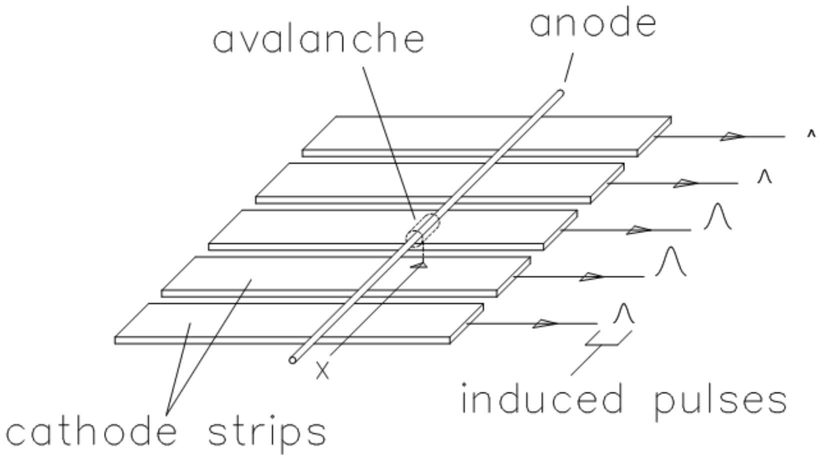
MSGC



Gas Detectors

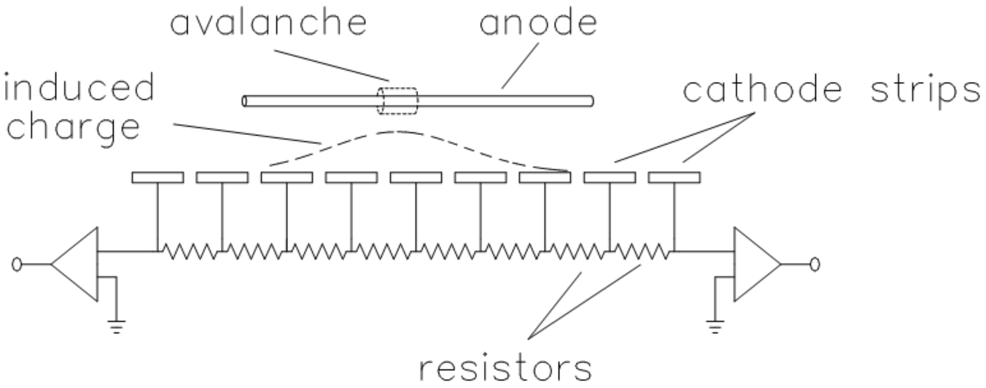
Individual readout

dead time = 100 ns

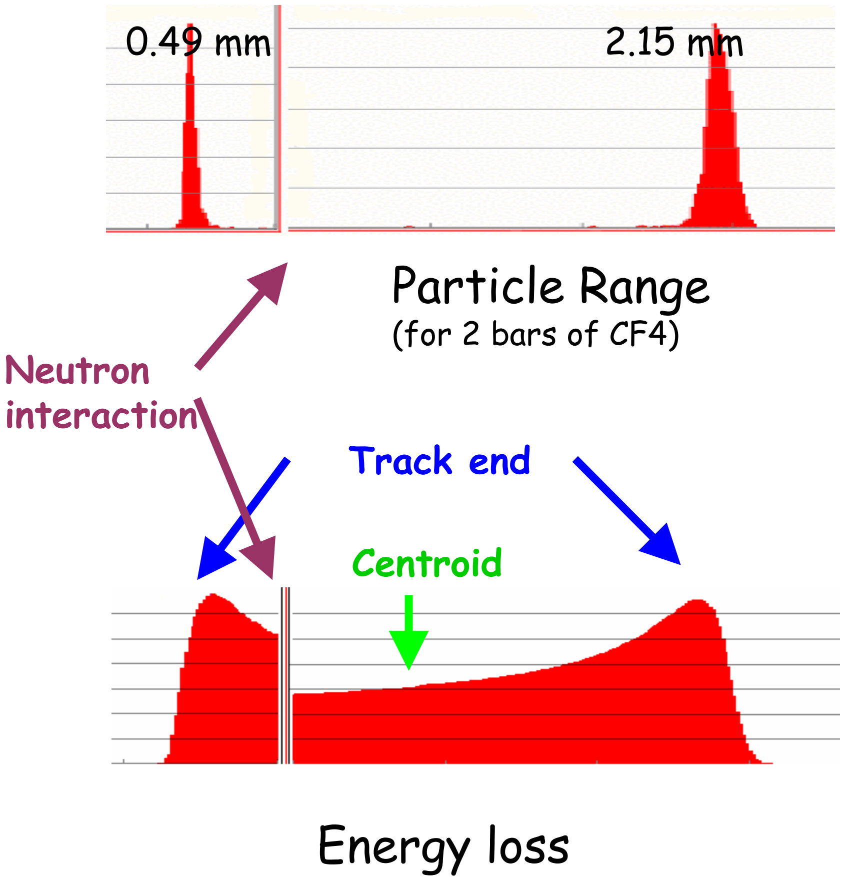


Global readout

Rise time
Charge division
Delay line
Dead time = 1 μs



A quenching gas (generally CF$_4$) is added to the converter gas to reduce the range of the ionizing particles



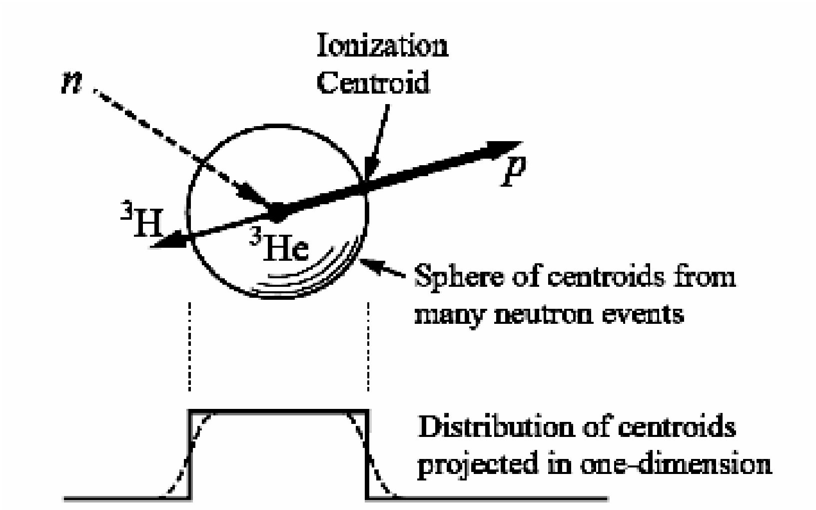
Particle Range
(for 2 bars of CF4)

Neutron interaction

Track end

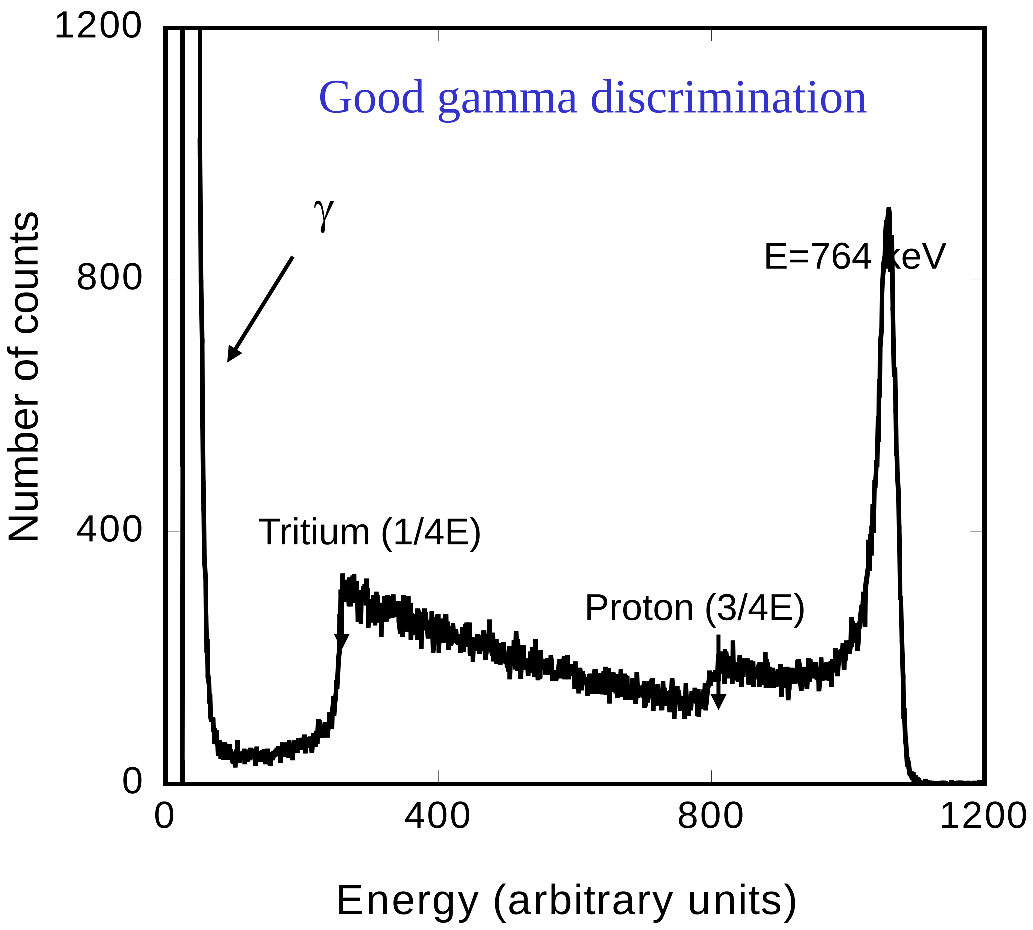
Centroid

Energy loss



Center of Gravity of the charges is the best estimation one can do to localize the neutron capture
Track end is faster but double the resolution

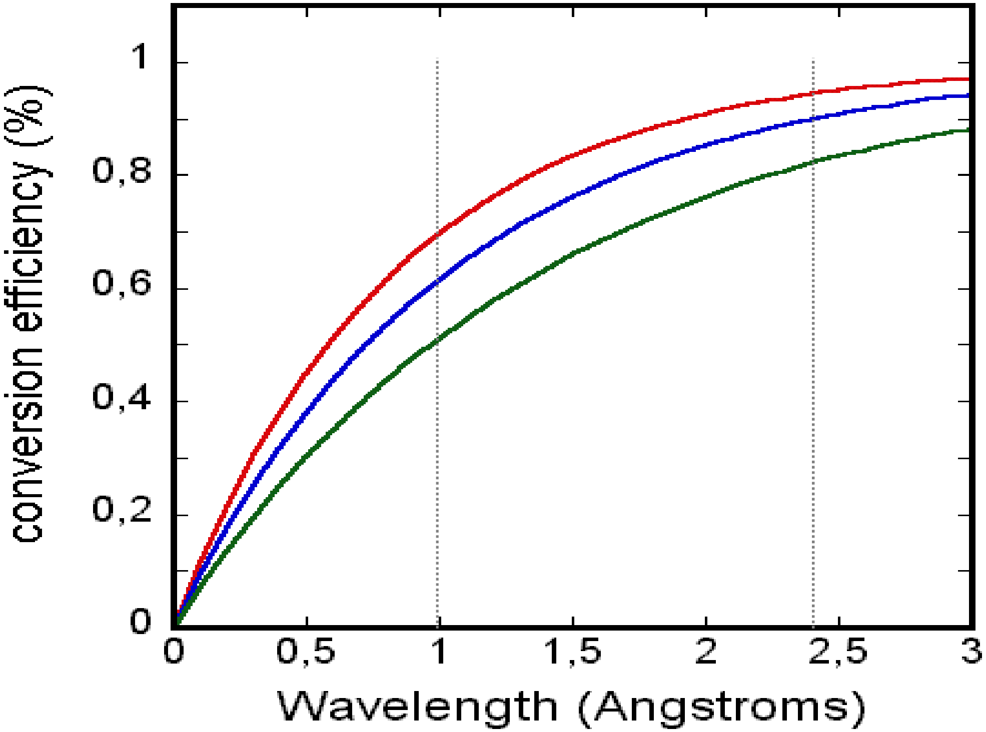
^{3}He : neutron converter



Pulse height spectrum measured with a single counter
and a low noise FET pre-amplifier

^{3}He : neutron converter

Capture in 3 cm of ^{3}He for 3,4,5 bars



$^3He + n \rightarrow p + {}^3H + 764$ KeV

5333 barns @ 1.8 angstroms (25 meV)

→ $\varepsilon = 14\%$ @ 1 cm.bar

$$\varepsilon = \exp[-\mu_{al} * ep_W] * (1 - \exp[-\mu_{3He} * ep_{Gap}])$$

$\mu = \rho * \sigma$

ρ *material density*

σ *interaction cross-section*

Efficiency requires high ^{3}He Pressure*gap

→ parallax error

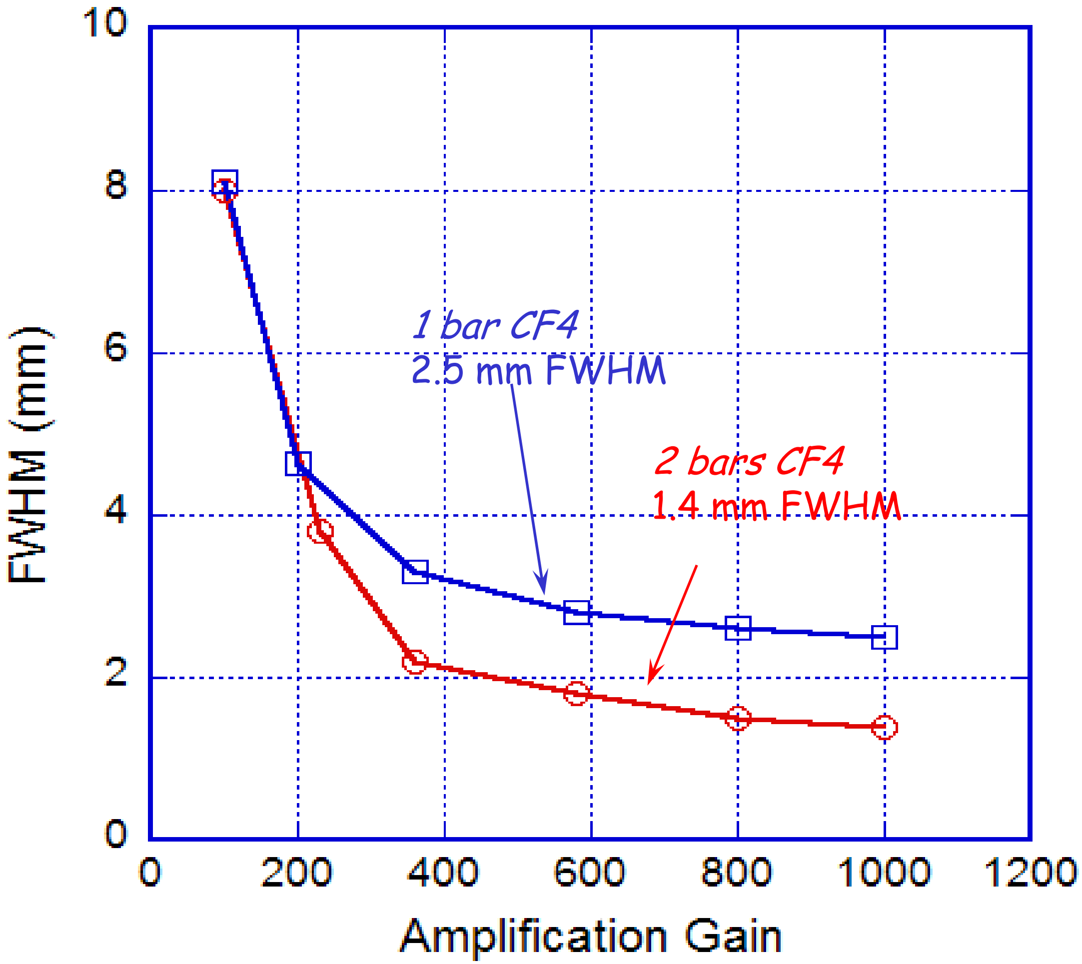
How to specify spatial resolution ?

A good detector for an instrument is the one which provides exactly the spatial resolution required, not better. Better resolution generally means useless extra cost or degraded performances on other parameters.

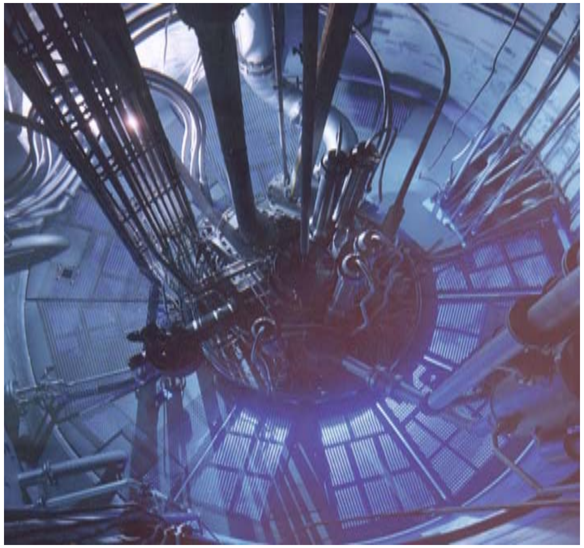
On a Single Crystal Diffractometer (SXD), one needs to correctly …
1/separate Bragg peaks,
2/measure the center of gravity, and
3/minimize the background under the peak.
- On monochromatic SXDs, large area detectors with a resolution 1-2 mm FWHM are needed.
- For biological crystallography, samples can only be produced in small sizes (< 1 mm^3); a large number of Bragg peaks are produced with low intensity → polychromatic beam + large solid angle (3Pi) detector with a resolution of < 1 mm FWHM.

Other typical spatial resolutions are:
1 mm for reflectometers
5-8 mm for Small Angle Scattering
20-30 mm for Energy spectrometers

Position resolution versus amplification gain and quenching gas pressure



The main actors in neutron detector development



ILL

93% ^{235}U fuel element

Flux = 1.2 x 10^{15} n/cm^2.s

ISIS

proton beam power : 0.16 MW

Pulse frequency : 50 Hz

Peak Flux = 2.3 x 10^{15} n/cm^2.s

Average Flux = 2 x 10^{12} n/cm^2.s

SNS

Proton energy: 1 GeV

Power : 1.4 MW

Pulse frequency : 60 Hz

Peak Flux : ISIS x 20

MSGCs
MWPC
Multitube

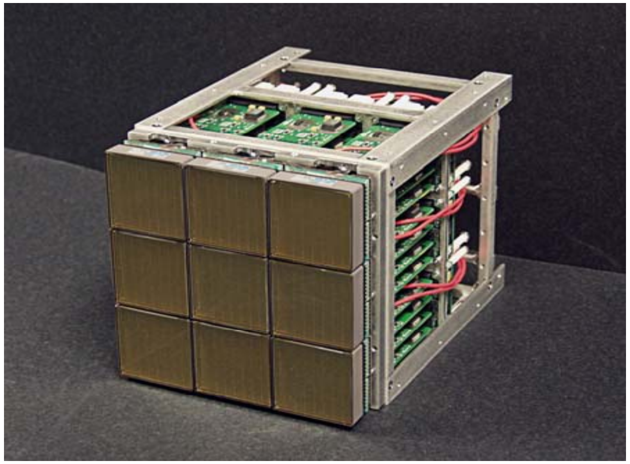
- **Scintillators coupled to WLS fibers**
- **Multitube**
- **Anger camera**

+ BNL (MWPC, pixel detector), Tokyo University (MSGC), J-PARC, FRM-II (Anger camera)…

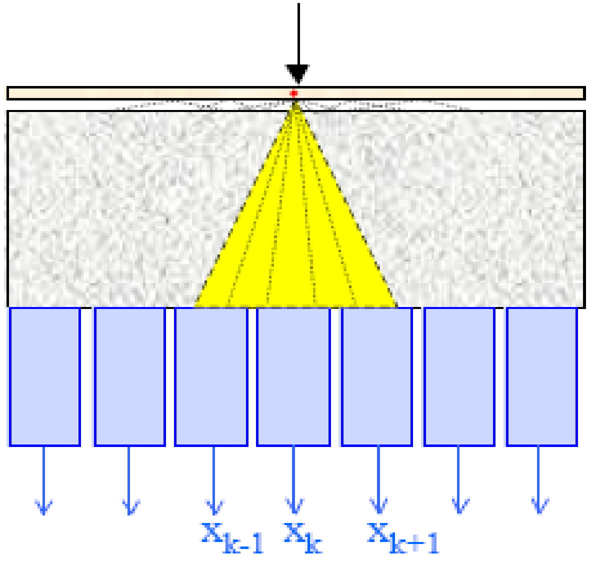
Anger camera

Anger camera with GS20 scintillators, developed at **SNS** for Crystallography instruments

Anode gain can vary by a factor of 3 which makes gain compensation necessary

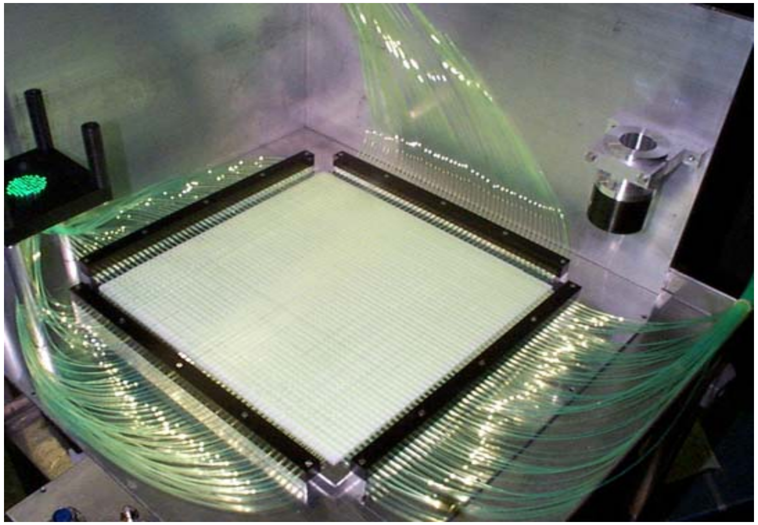


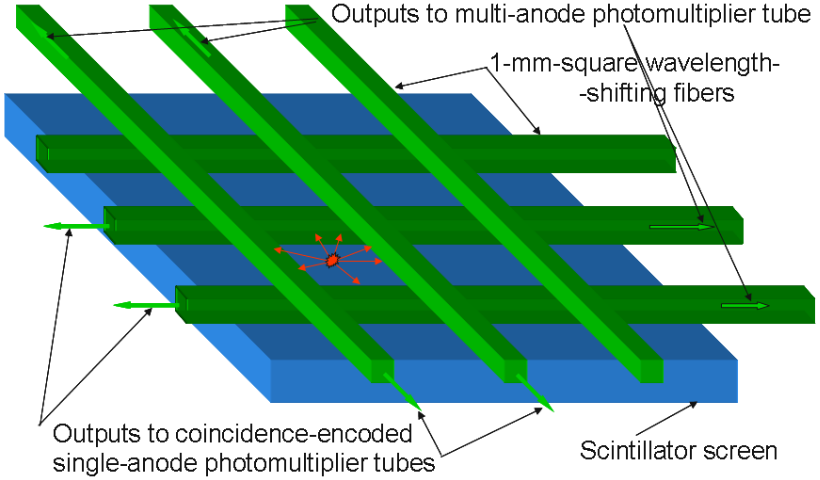
a camera has 9 PMTs each with 64 anodes



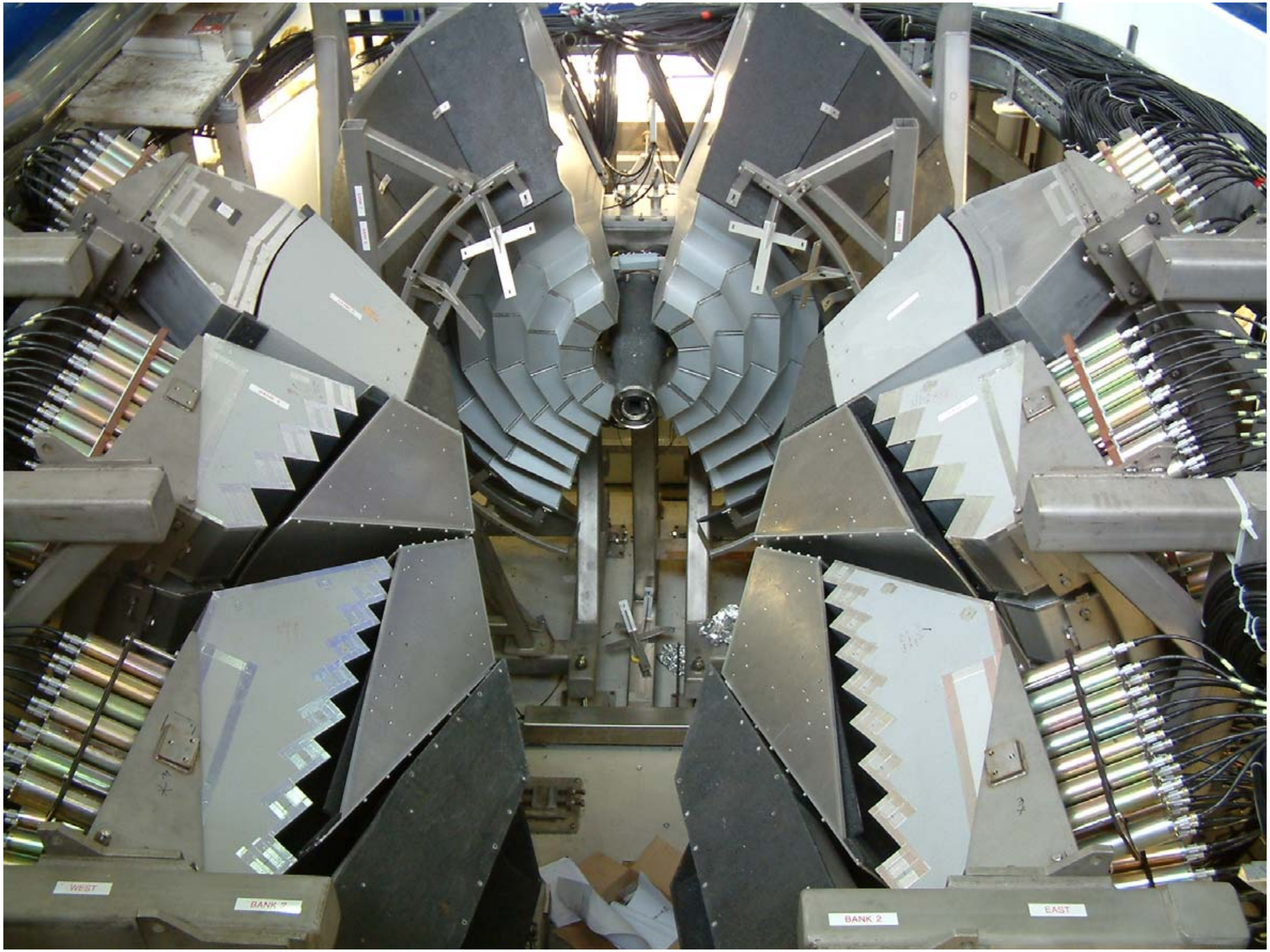
Crossed-Fiber Scintillation Detector Design Parameters

- Size: 25-cm x 25-cm.
- Thickness: 2-mm.
- Number of fibers: 48 for each axis.
- Multi-anode photomultiplier tube: Phillips XP1704.
- Coincidence tube: Hamamastu 1924.
- Resolution: < 5 mm.
- Shaping time: 300 nsec.
- Counting-rate capability: ~ 1 MHz.
- Time-of-flight resolution: 1 μsec.





ISIS



MSGC

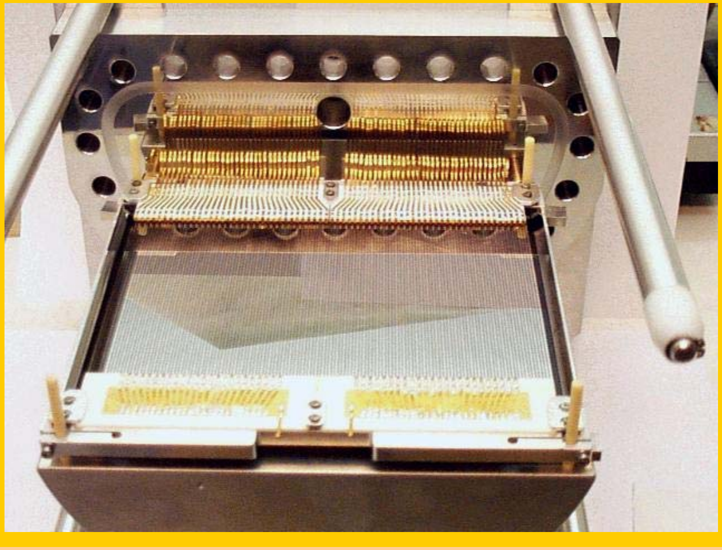
Advantages of Microstrip Gas Chambers :
Energy resolution
Position resolution
Counting rate

but ….

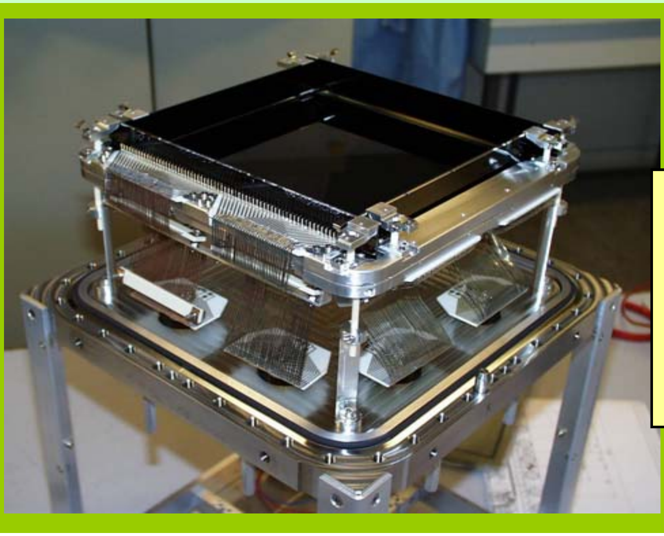
- Gas purity, and substrate cleanliness are crucial
- substrates are limited in size (difficult to build large 2D detectors)
- temperature must be controlled at 1° to avoid variation of gain

MSGC

D20 powder diffractometer (since Feb 2000)
1D localisation
48 MSGC plates (8 cm x 15 cm)
<u>Angular coverage : 160° x 5,8°</u>
Position resolution : 2.57 mm (0,1°)
5 cm gap; 1.2 bar CF_4 + 2.8 bars ^3He
Efficiency 60% @ 0.8 Å



D4 powder diffractometer (since 2000)
Modular MSGC (9 modules)
145° Horiz. (2 scans) x 5.7° Vert.
Position resolution : 2.5 mm (0.14°)
Gas pressure : **15 bars** ^3He + 0.3 bar CF_4
Detection efficiency : 90% (@ 0.7 Å)



Bidim19
Position resolution : 3 mm
Useful area: 192 mm x 192 mm
94% efficiency at 2.4 Angstroms
used on D19 during 2 years

MWPC (Multi Wires Proportional Chamber)

Curved 2D MWPC for Single Crystal Diffraction

Very large angular coverage: 120° (h) x 29° (v)   L2 = 75 cm

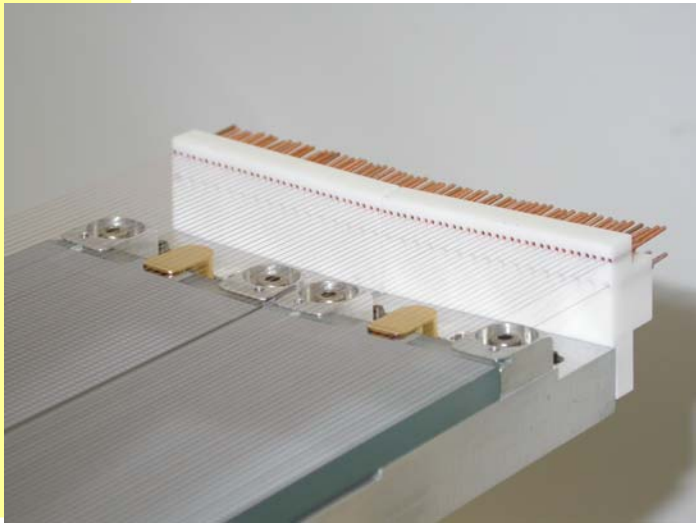
40 detection elements comprising 16 anode sensing wires (h coord), 32 field wires, and a glass electrode with a chromium layout for charge division (v coord).

5 bars of 3He + 1 bar of CF4

Efficiency: 80 % @ 2.5 Angstroms

Spatial resolution : 2.5 mm (h) x 3 mm (v)

Electrostatic lens to reduce the Parallax error in the vertical direction.



Running on the D19 Instrument since 2005

Bidim26 MWPC

Sensitive area : 26 cm x 26 cm

Spatial resolution = 2 mm x 2 mm

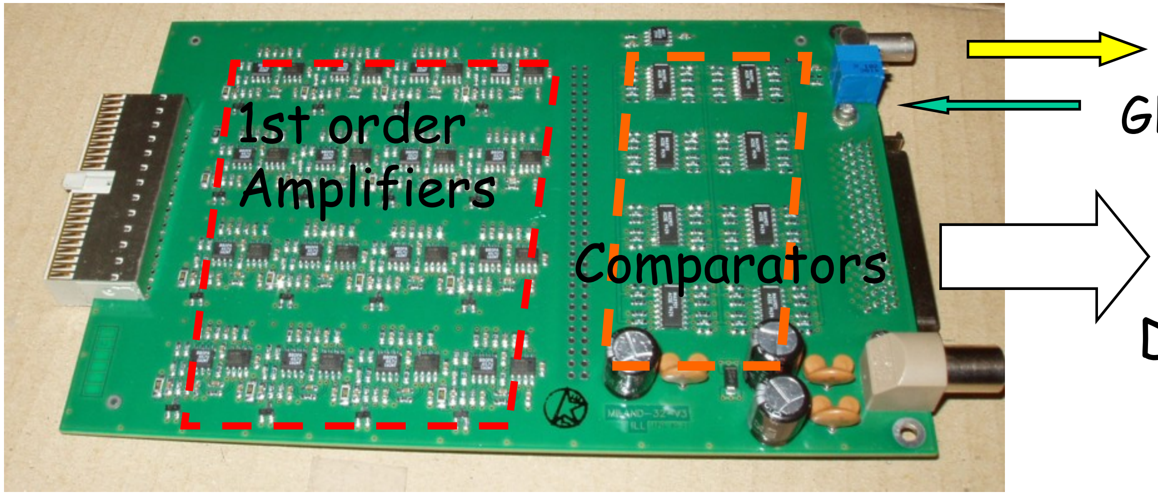
2*128 individual channels readout

Count rate : 3.10^5 counts/sec global

3.10^4 counts/sec per pixel

Individual channel Readout Electronics

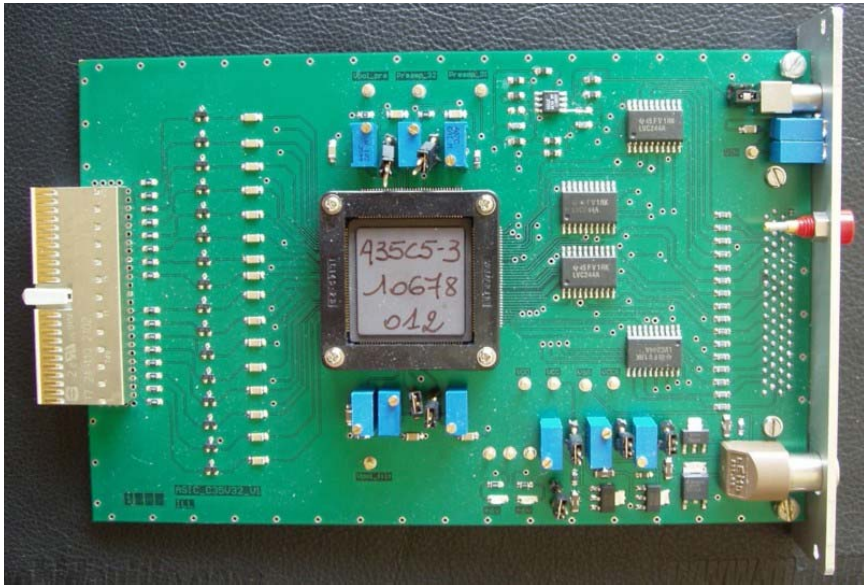
Amplifier mother board



Analog sum

Global Threshold

32 Parallel
Digital Outputs



C35V32_v1 ASIC:

-Fast pre-amplifier with RC = 20 ns

-Auto Dynamic offset cancellation

-Balance comparator

-Anode or cathode readout

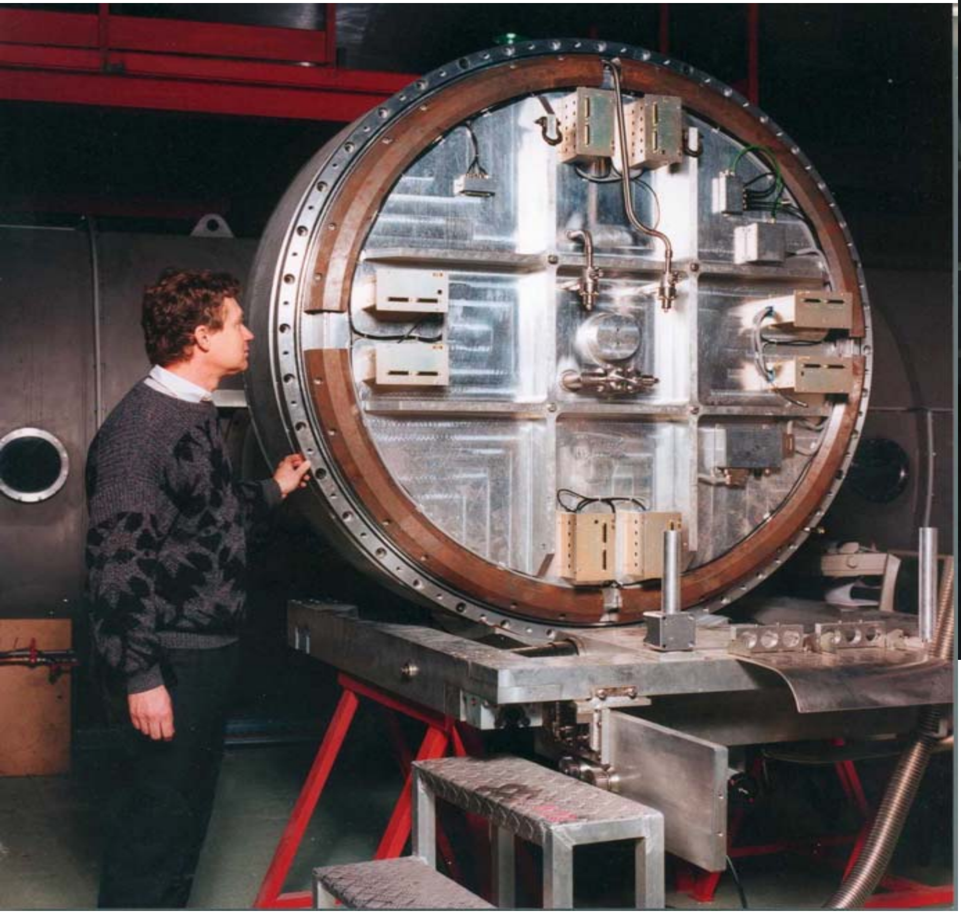
-Good linearity

-low noise

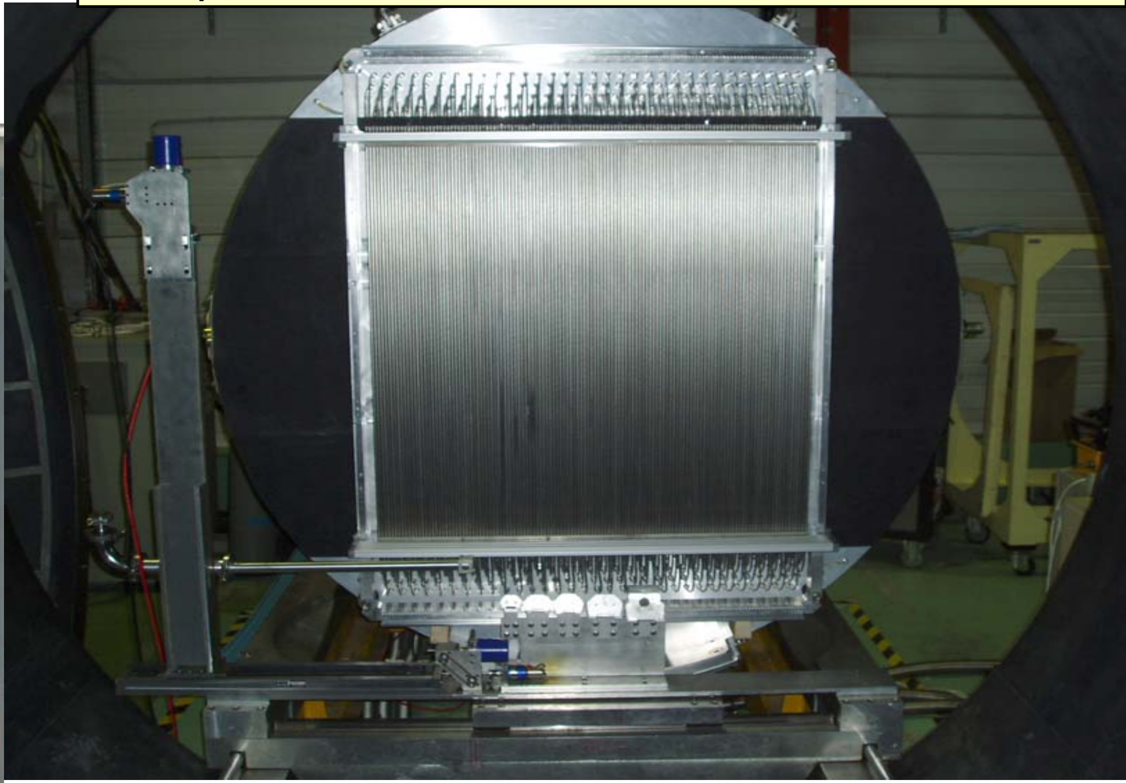
PSD for SANS

From standard MWPC …

XY measured by coincidence of 2 orthogonal wire frames



… to position sensitive counter tubes

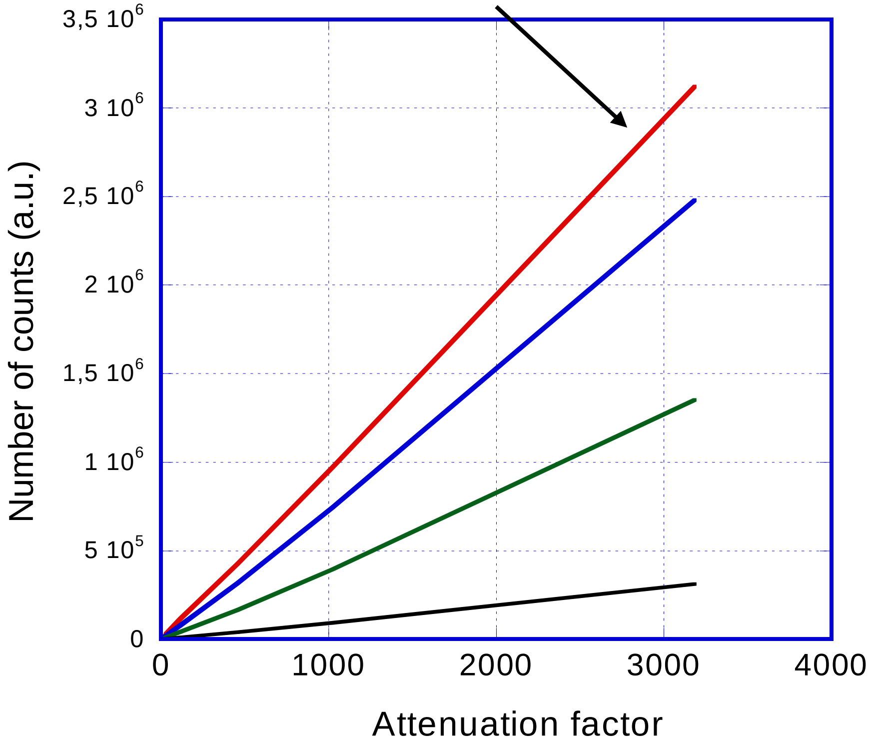


128 PSPC covering 1 m^2 of sensitive area.
Position measurement by charge division
Tube diam.: 8 mm. Pressure: 15 bars
Efficiency: 75 % @ 5 Angstroms

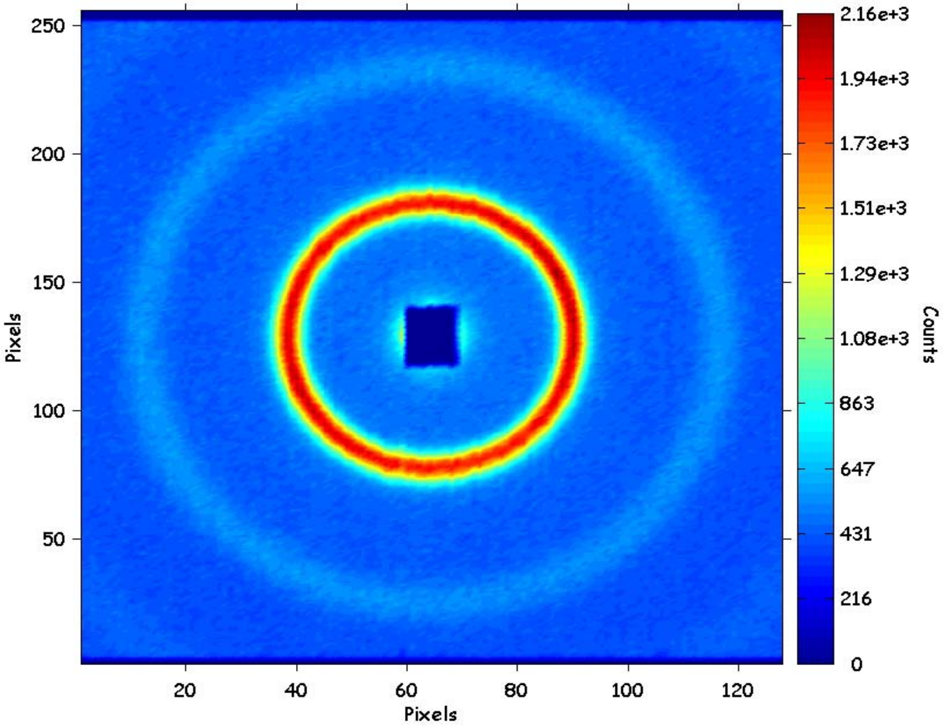
- Cost is ~2 times less than for a MWPC of equivalent size

D22: counting rate performance

No deviation from linearity at 3 MHz !



- ✠ The multi-PSPC improves the counting rate capability of the previous MWPC of D22 by a factor of 50.



Diffraction pattern of a AgBe powder sample

- ✠ Other detection parameters are maintained (size, spatial resolution, uniformity, gamma sensitivity)

^{3}He detectors for neutron reflectometry

MULTITUBE

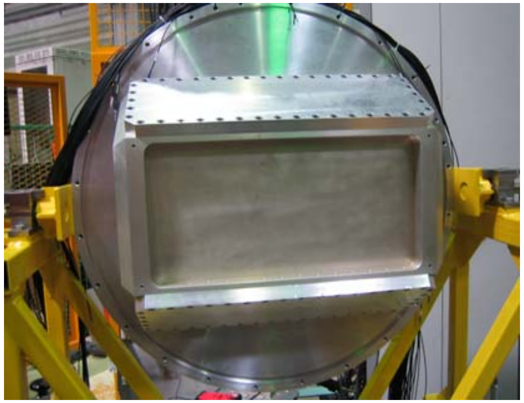
Sensitive area : 25cm x 45cm

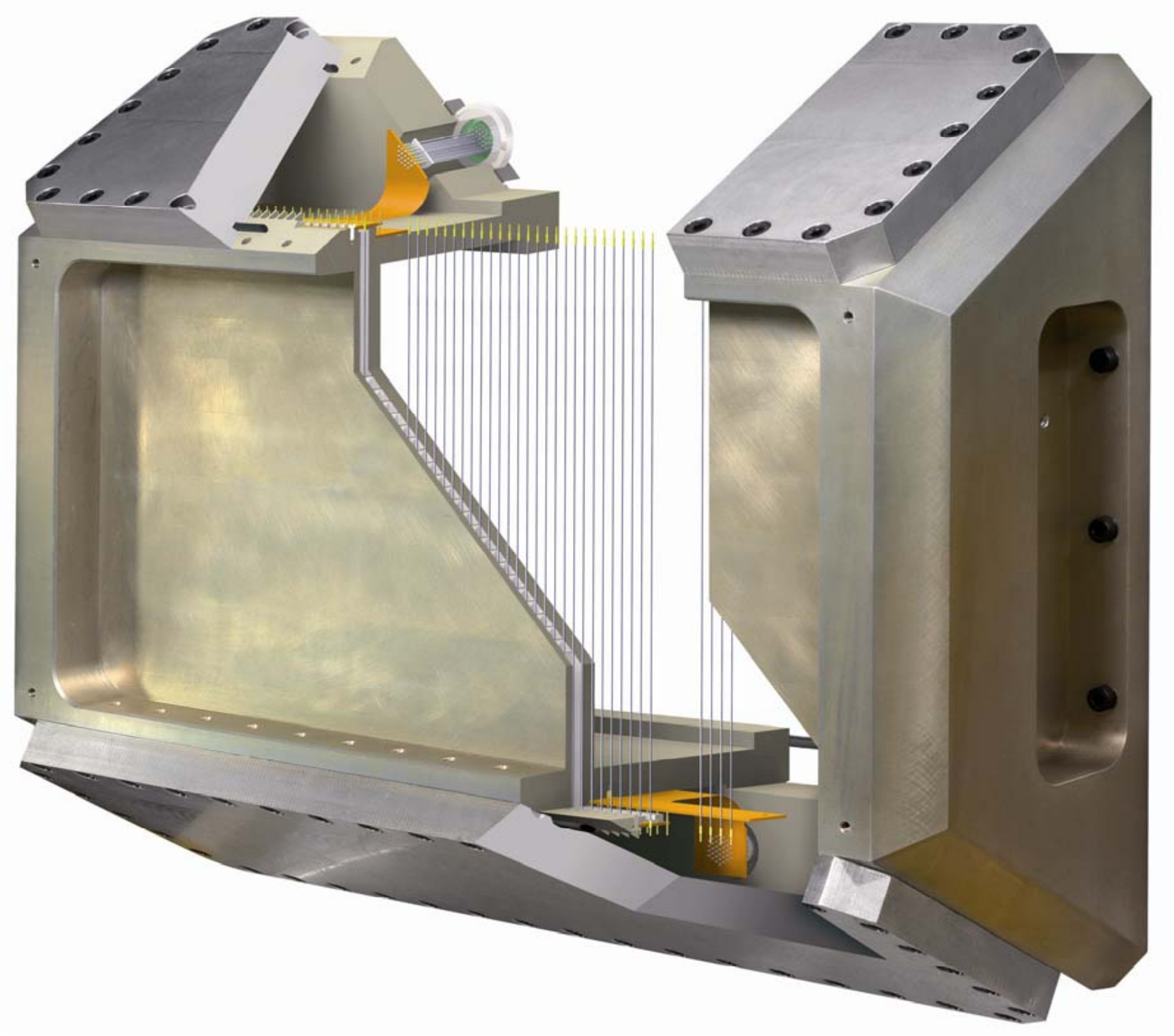
Parallel charge division readout

Spatial resol: 1.5 mm (along tube) x 7 mm

Peak Count rate : 10^6 counts/sec global

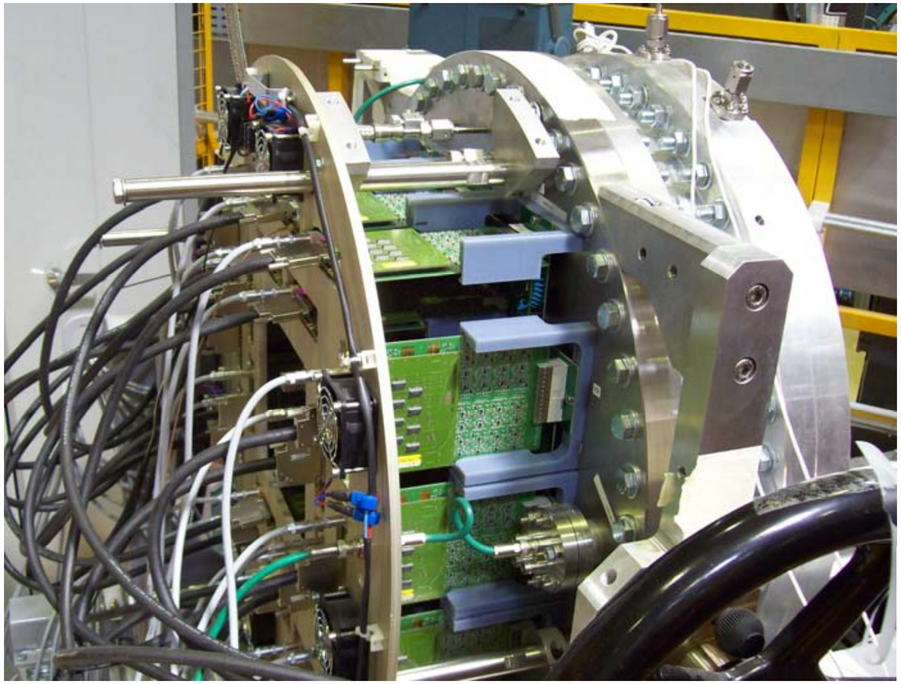
2.10^4 counts/sec and per mm of anode wire





MILAND (Millimetre Large Area Neutron Detector)

MWPC for Single crystal diffraction and reflectometry



European collaboration (FP6)

36 participants from 10 institutes

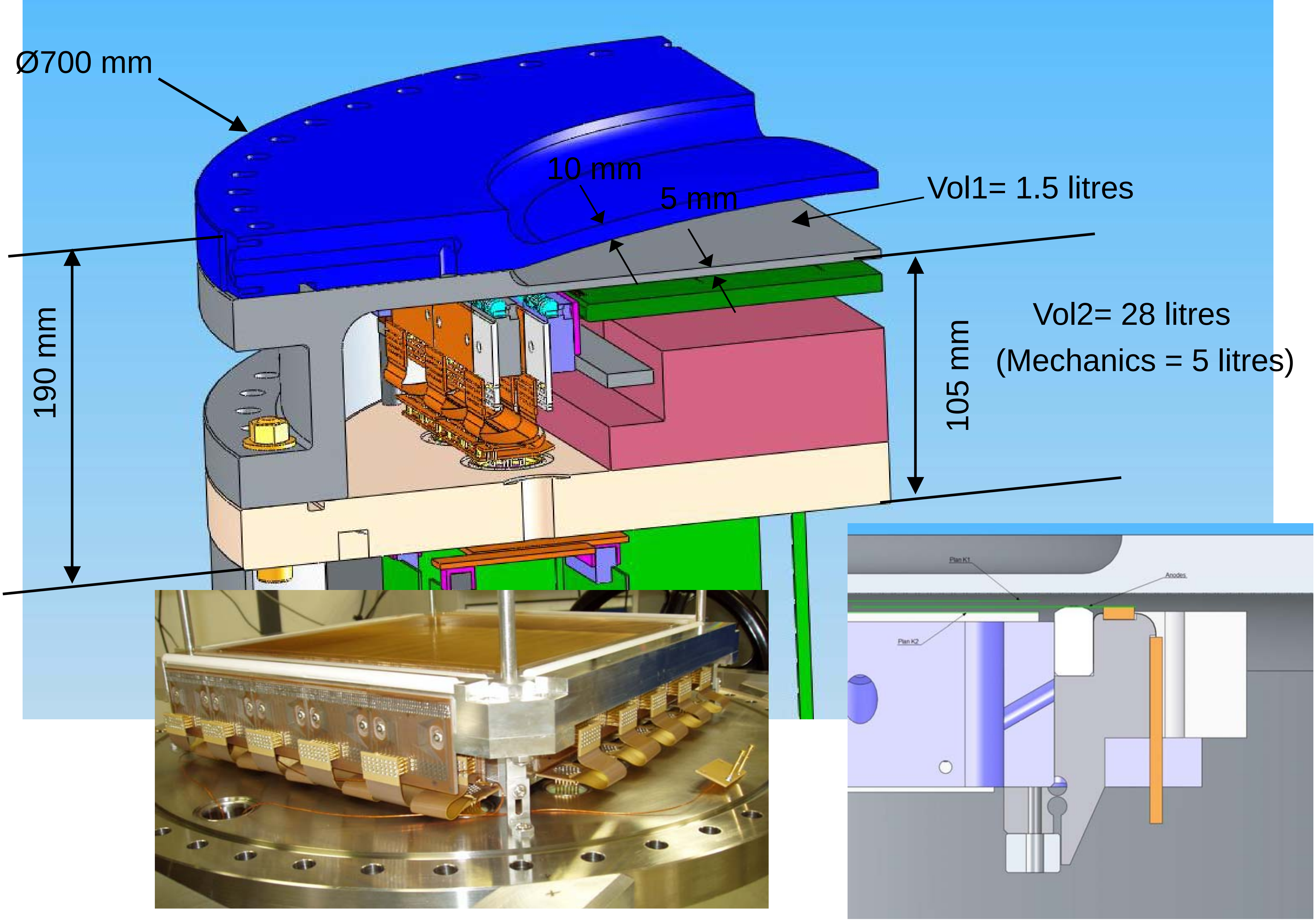
32 cm x 32 cm sensitive area

1 mm readout pitch (640 individual channels)

5 mm conversion gap (+ 20 mm optional)

15 bars gas pressure (13.5 3He + 1.5 CF4)

FPGA TOT (Time-Over-Threshold) processing electronics

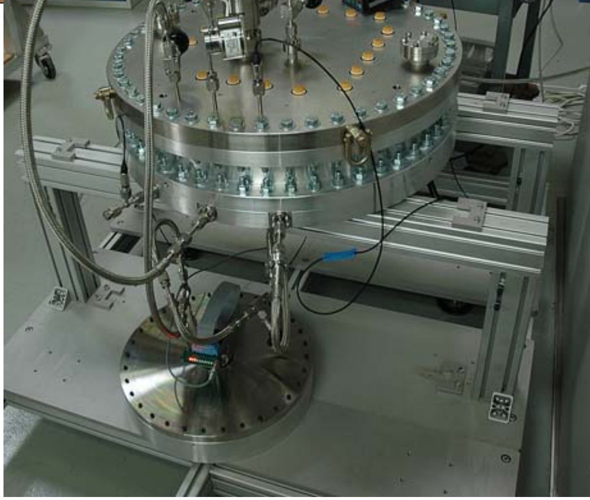

Ø700 mm
10 mm
5 mm
Vol1= 1.5 litres
190 mm
105 mm
Vol2= 28 litres
(Mechanics = 5 litres)
Plan K1
Anodes
Plan K2

pressure vessel fabrication

TIG welding of 20 HV 37pts feedthroughs connectors and gas feedthroughs

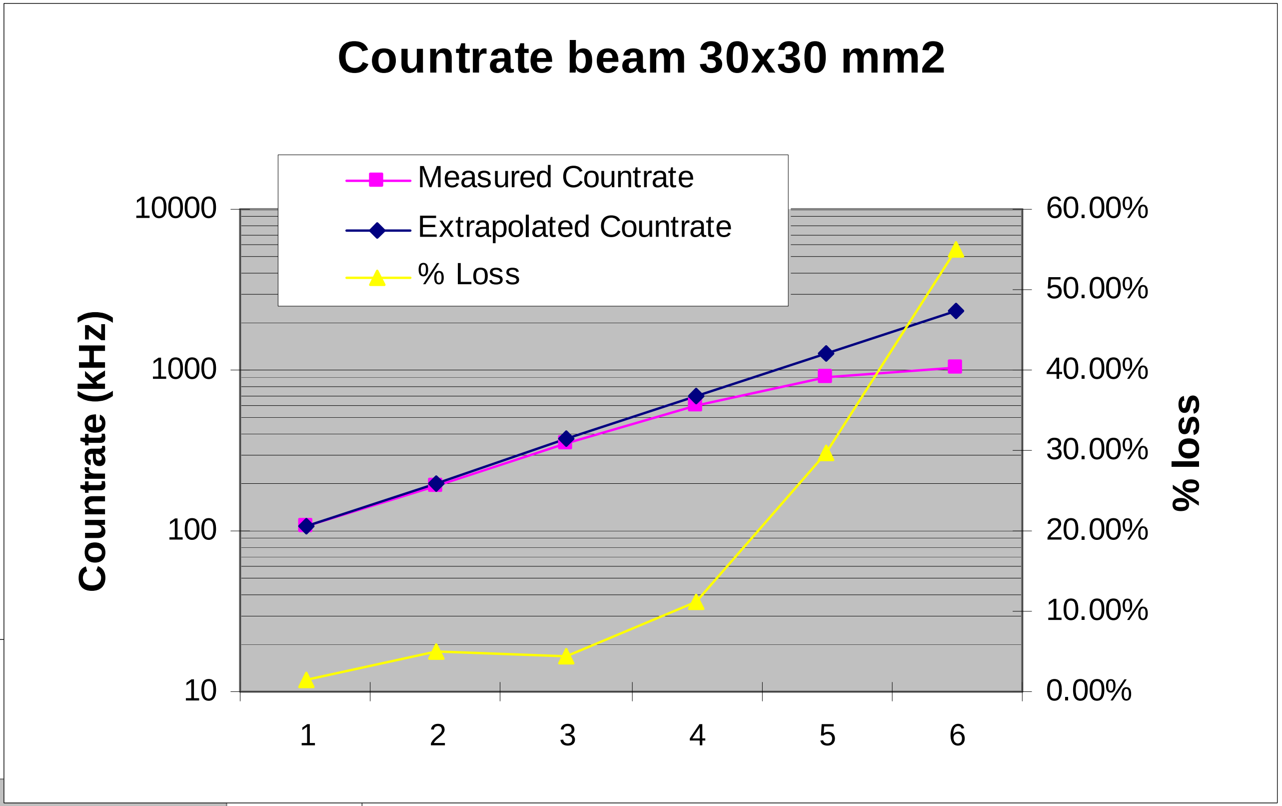
Gas tightness control

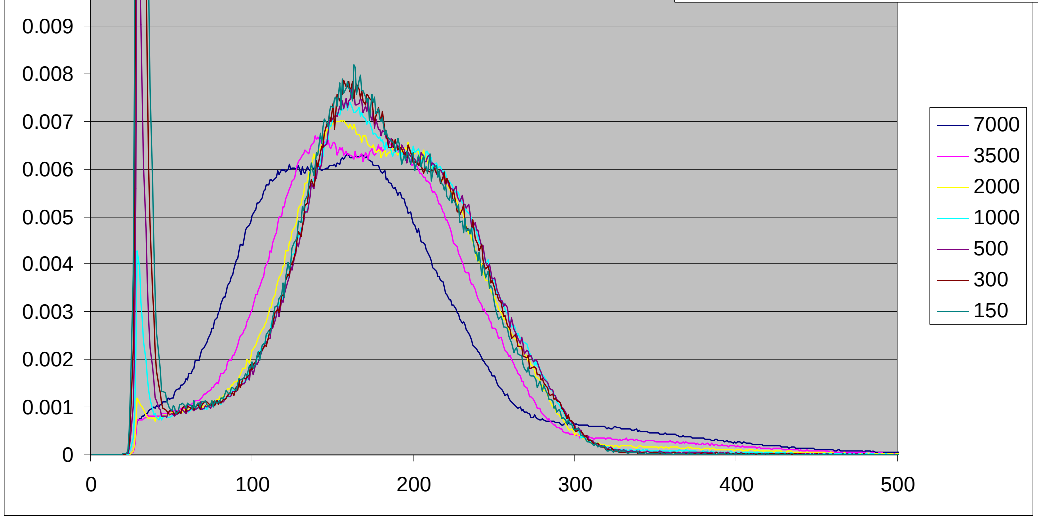
Temperature pressure compensation



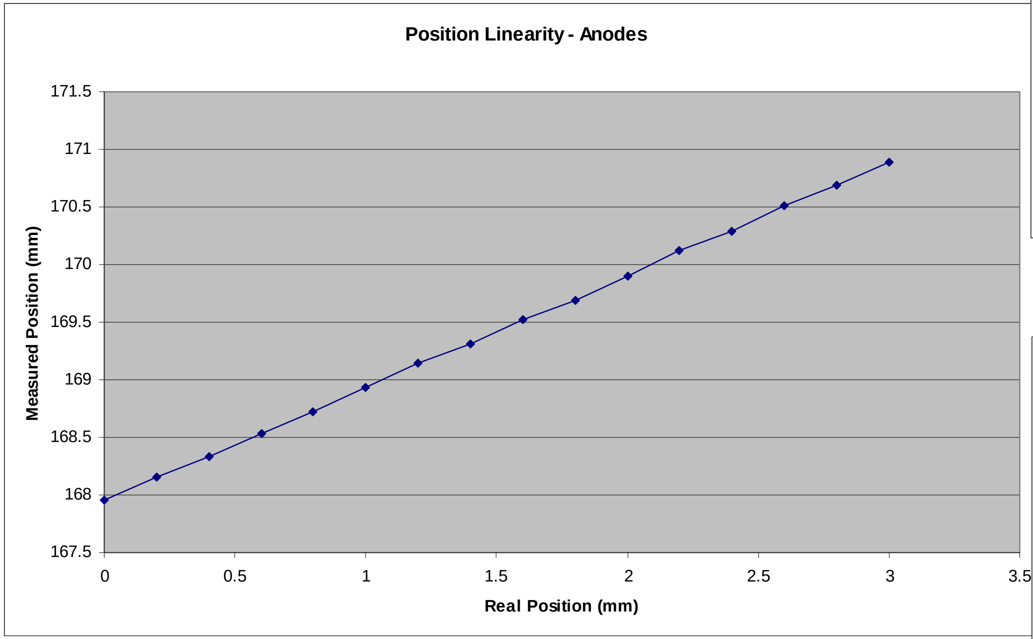
Pressure test (0 to 21.5 bar)

Space charge effect and counting rate

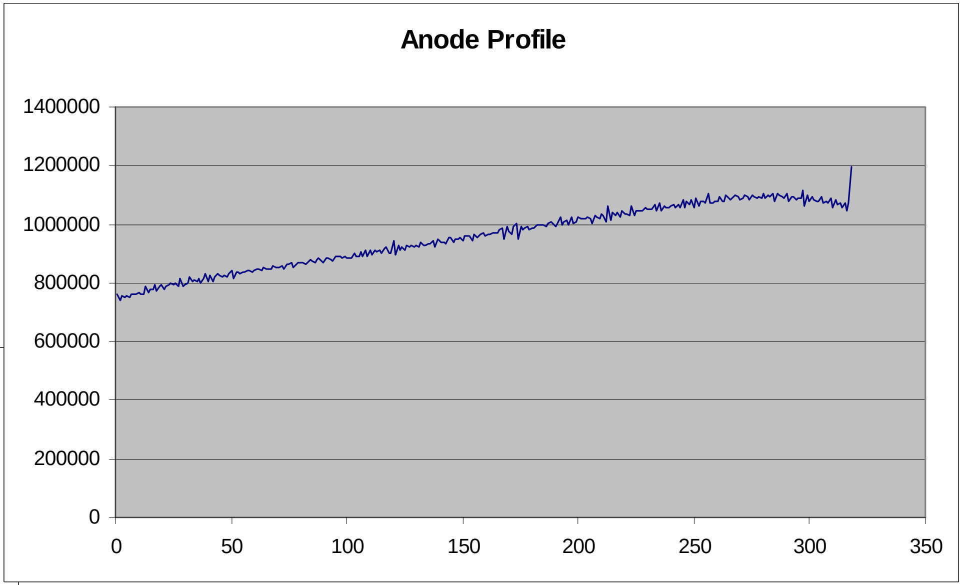




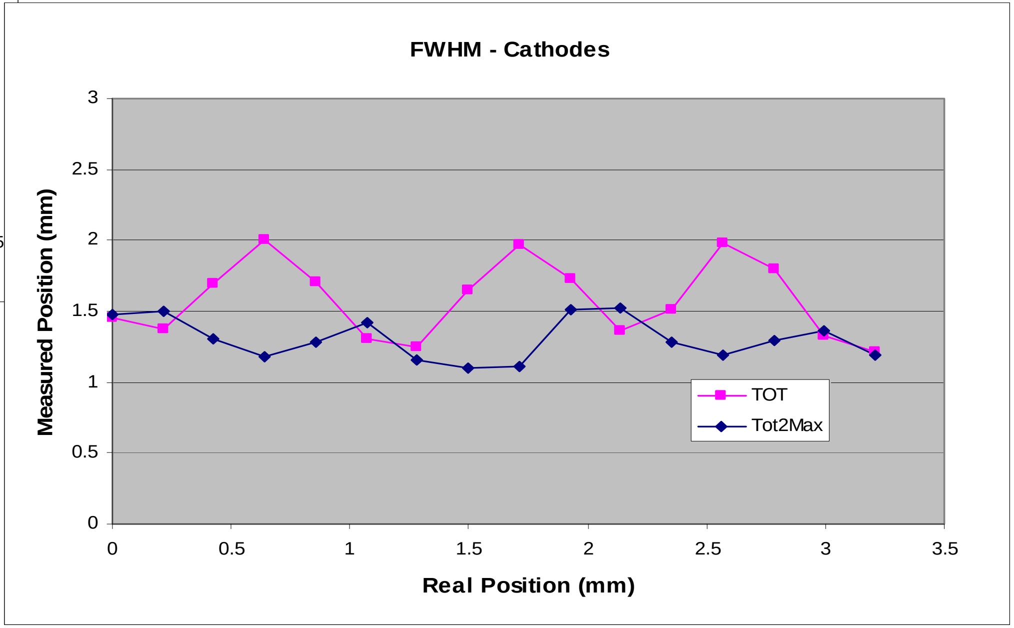
Linearity



Deviation from linearity
11 μm r.m.s. on the anodes
15 μm r.m.s. on the cathodes

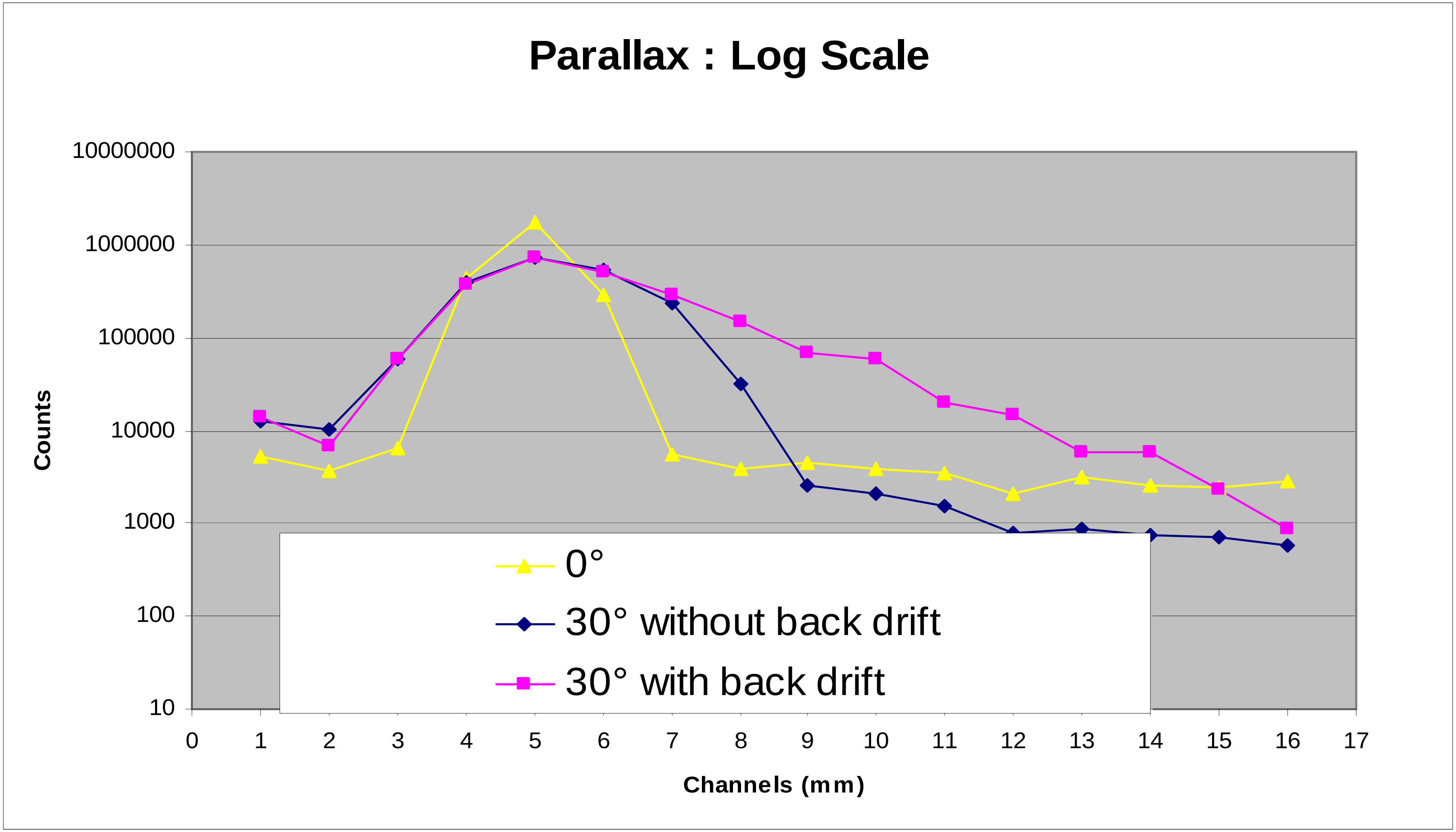


Uniformity



Spatial resolution

Parallax : Log Scale



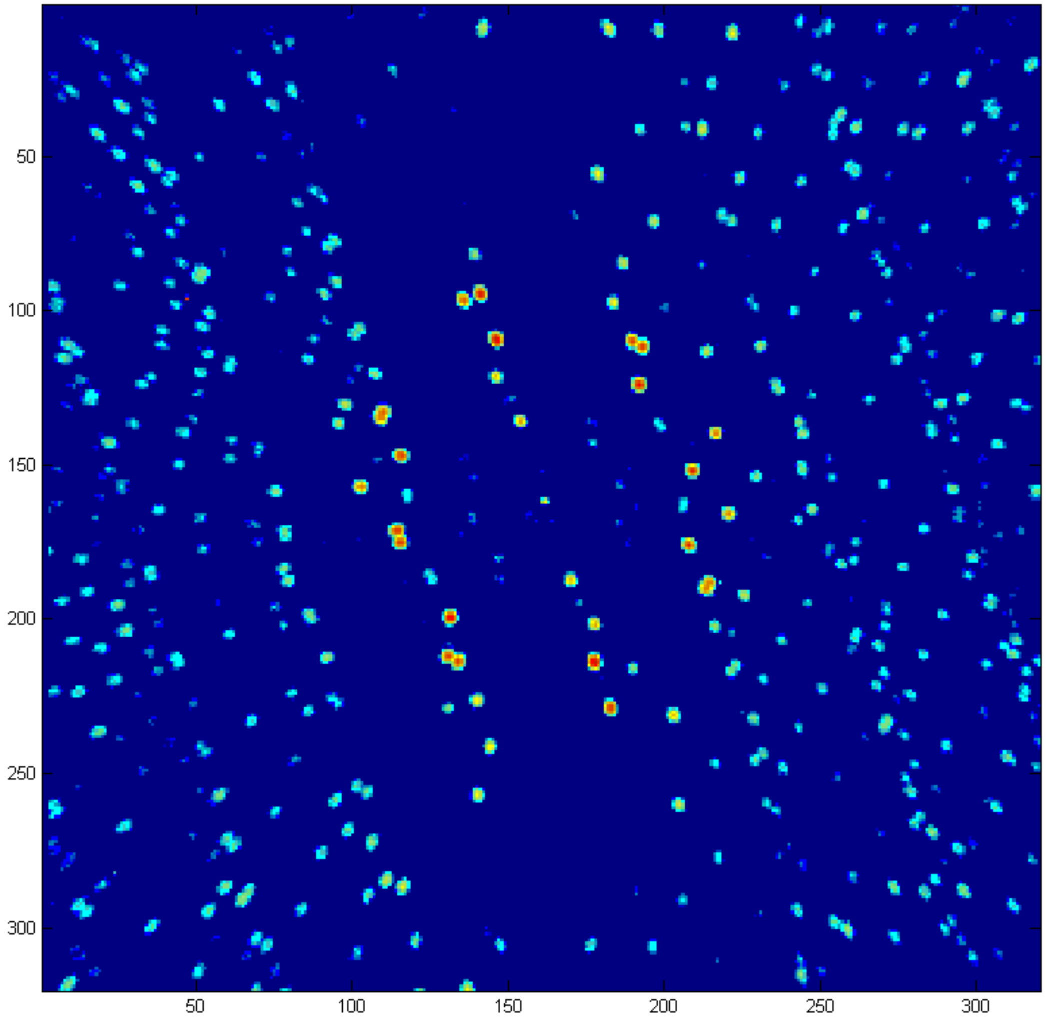


Image obtained on the D16 instrument with a lysozyme crystal, by superimposing images obtained during an angular scan. The detector was mounted at 35 cm from the sample. The neutron flux on the sample was 4 * 10^4 n/sec, and the total acquisition time 16 hours.

Detector limitations on new spallation sources

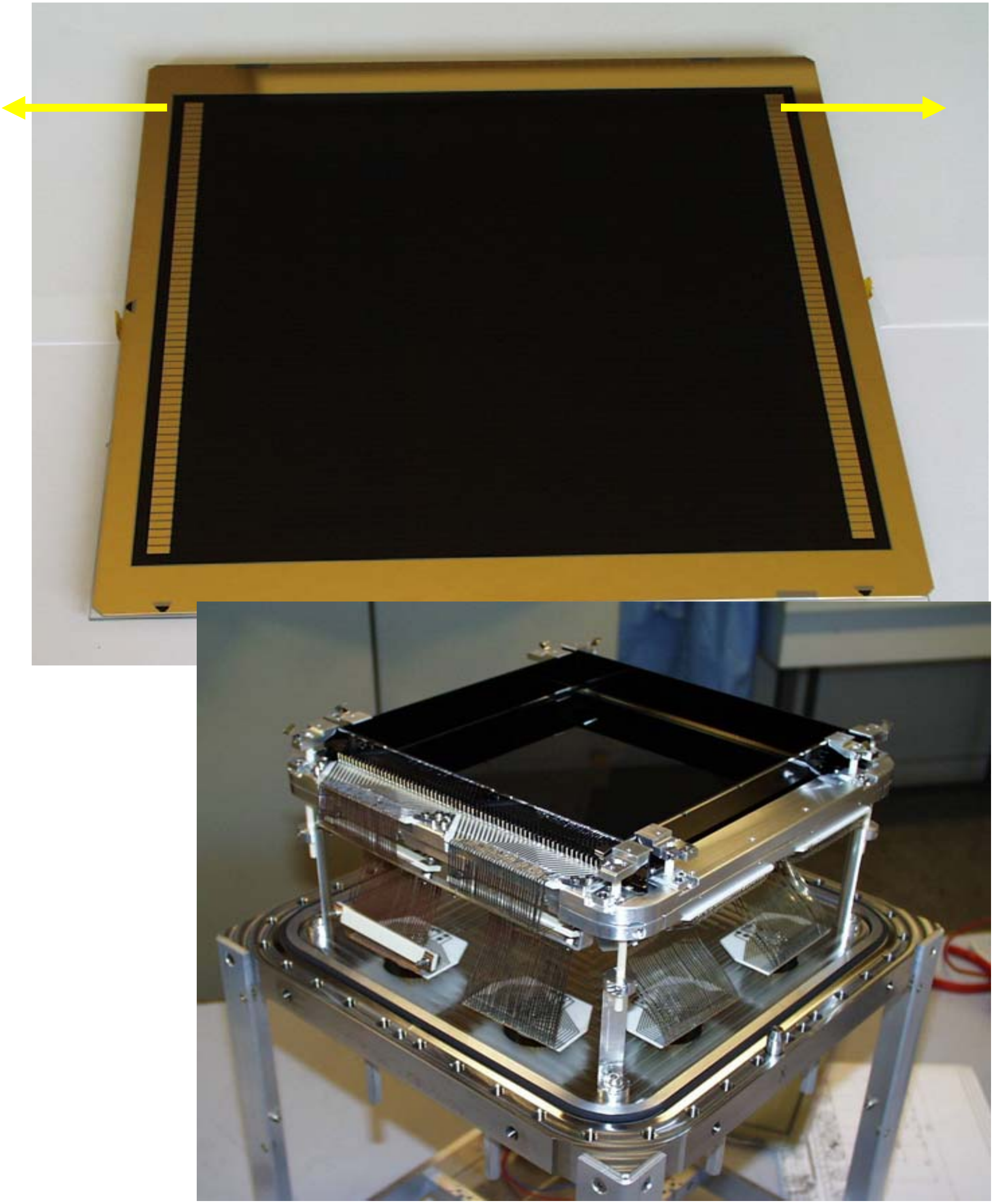
R&D to increase the instantaneous data rate capabilities and/or the spatial resolution of the detectors will be critical for realizing the full capabilities of many of the STS instruments." (SNS second target station working group, 2008)

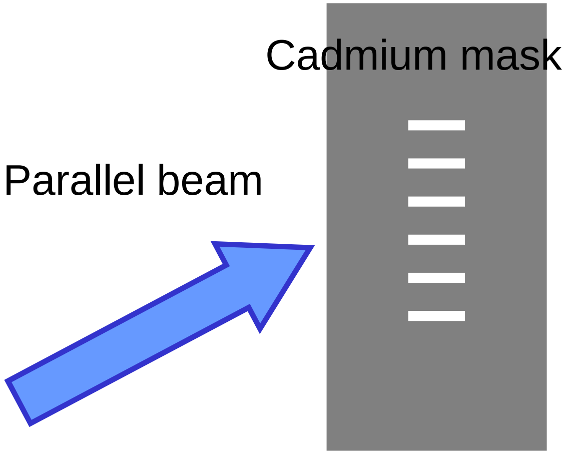
Shortage of 3He gives an additional (decisive) reason for supporting R&D on detectors

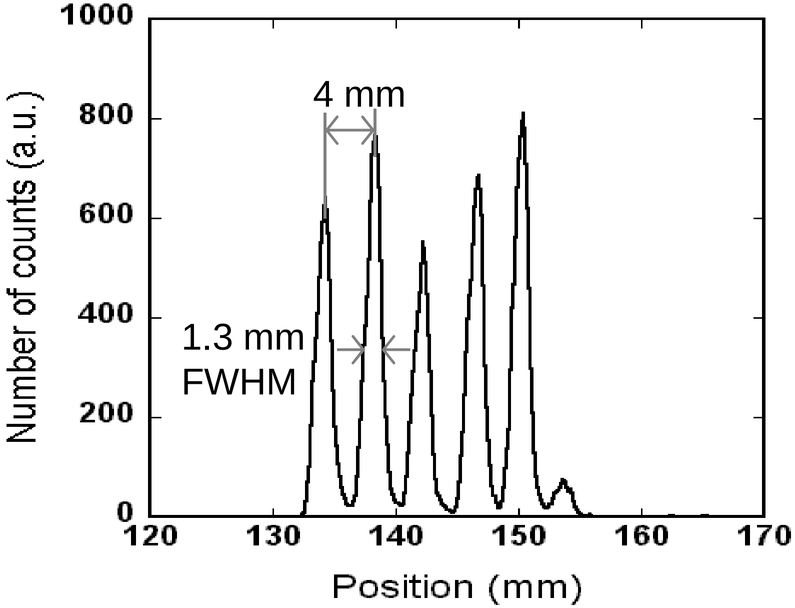
Some prospects

- MSGC Charge division Parallel readout
- Anger type GSPC-MSGC
- Multiblade

Parallel charge division readout with a MSGC (Micro Strip Gas Chamber)

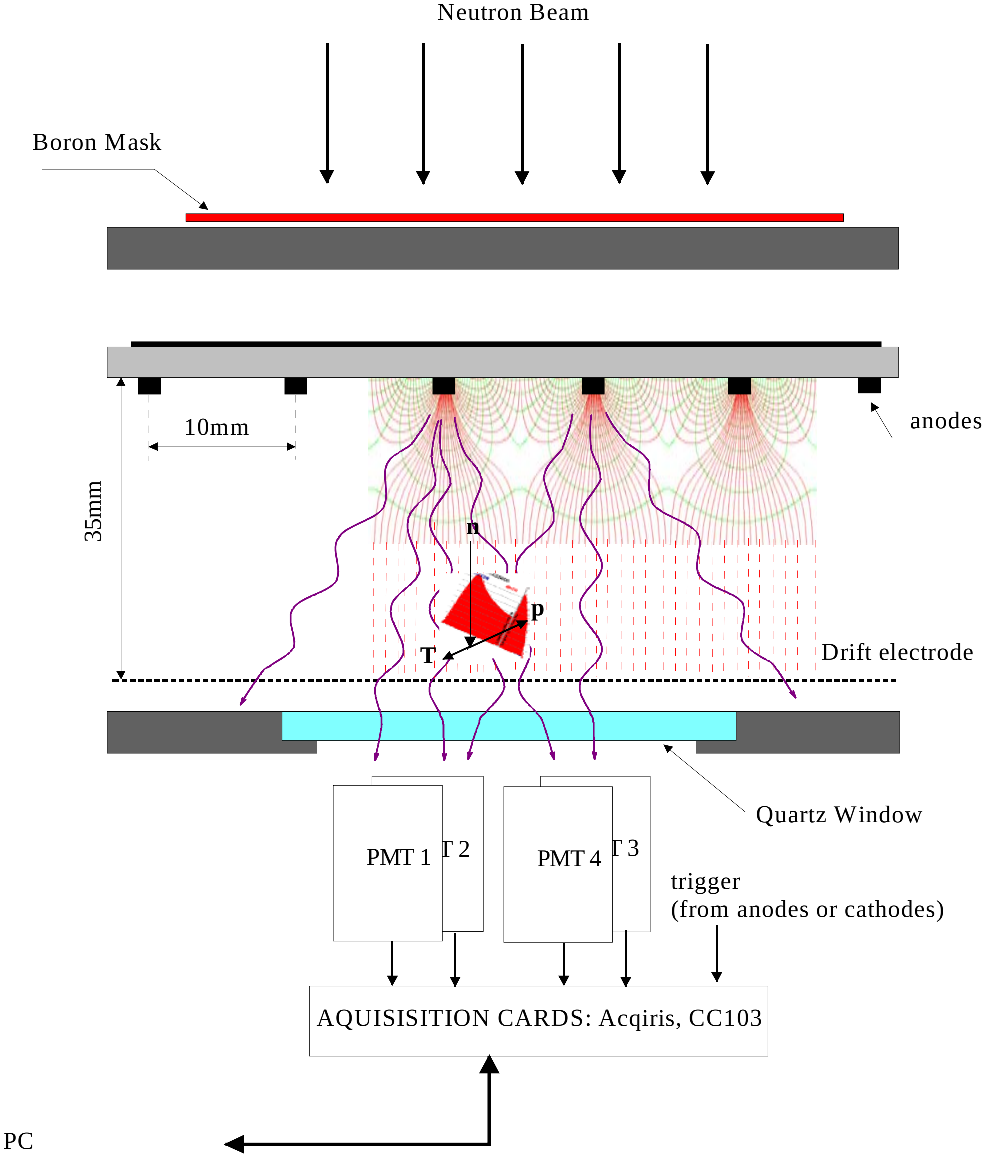


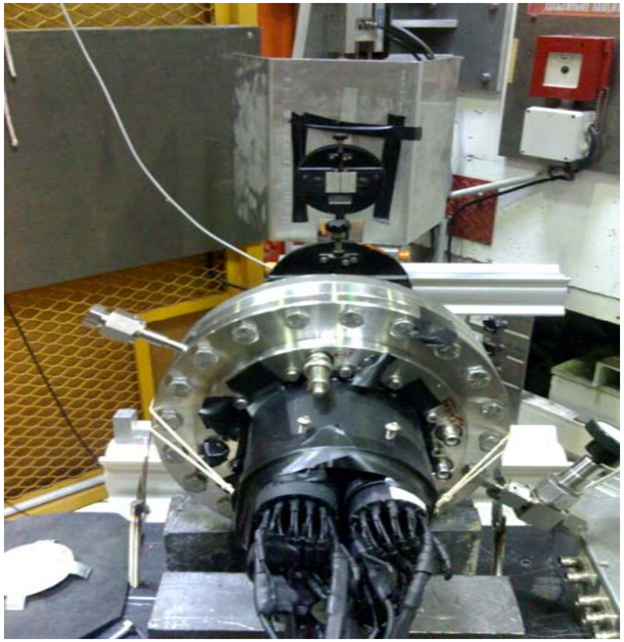




Resolution: 1.3 mm FWHM
(= limit of the stopping gas at 2 bars CF_4)

Anger type GSPC-MSGC

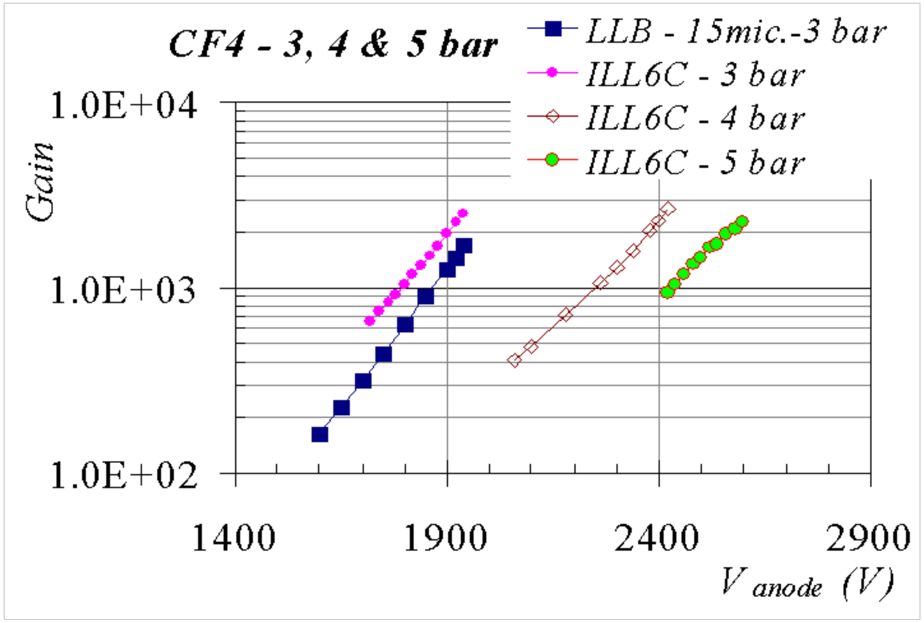




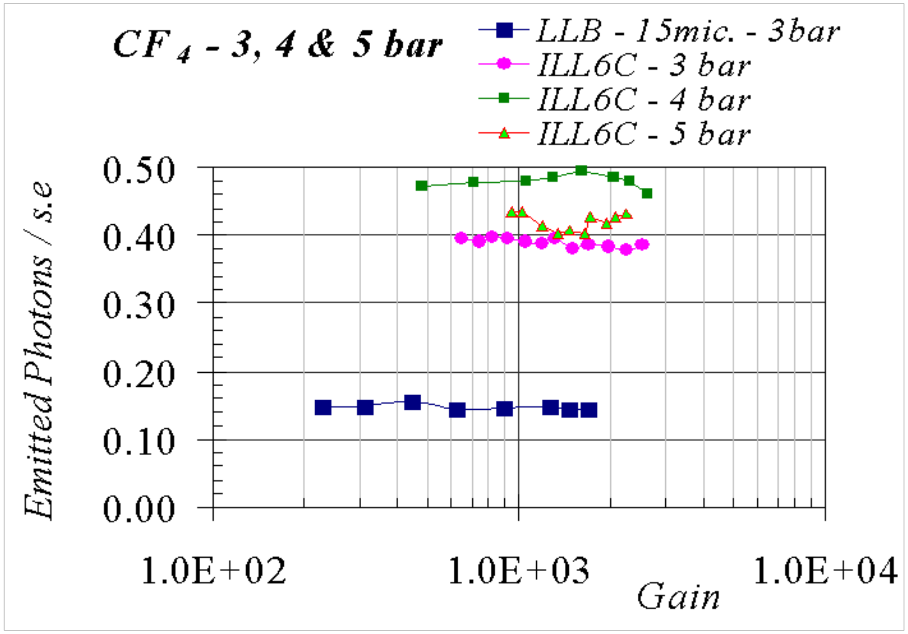
Transparent MSGC with ITO metallization

MSGC at High pressure

- ❑ Measurements at 3, 4 and 5 bar CF_4

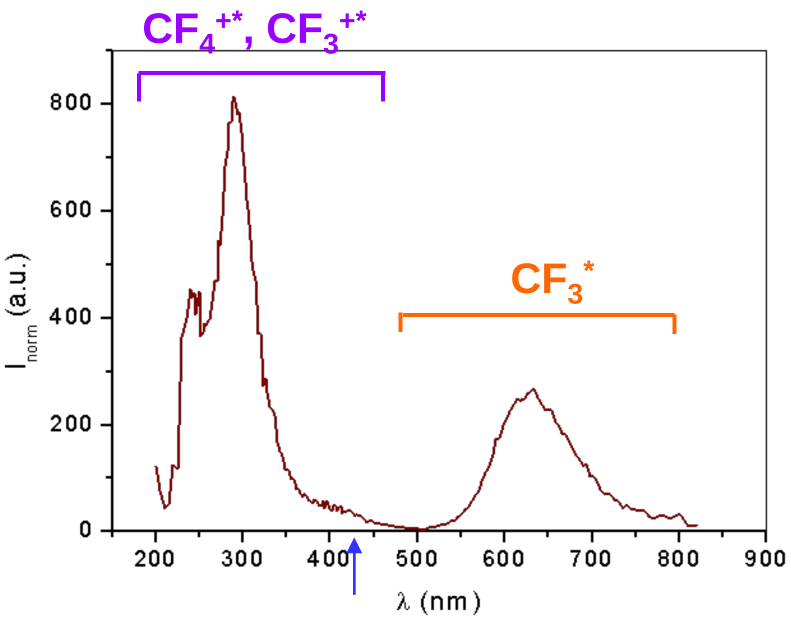


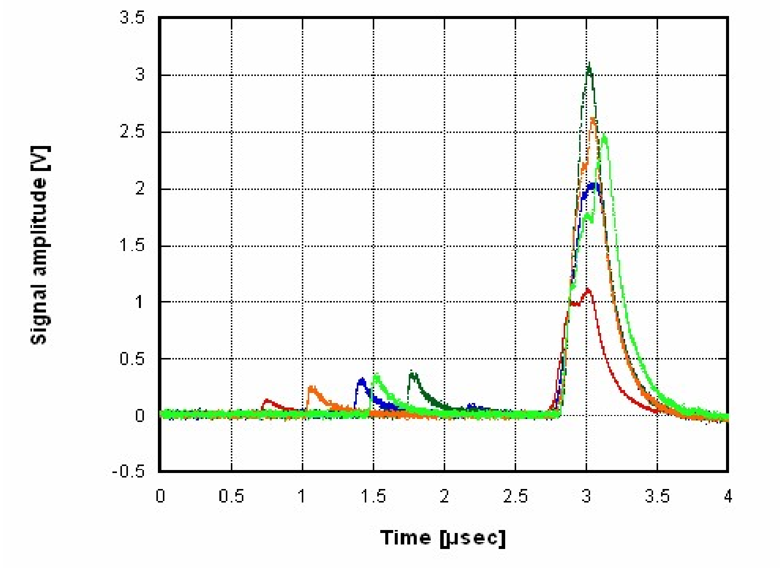
Charge gain *versus* anode voltage



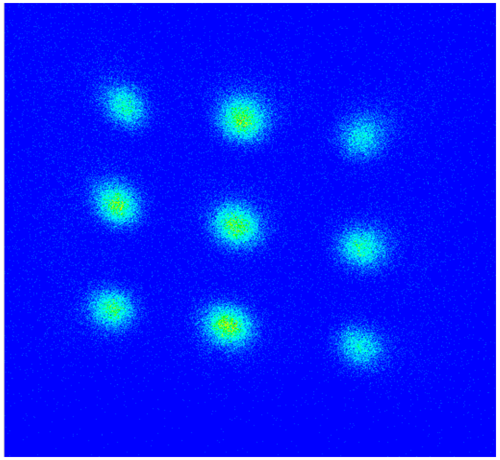
Number of emitted photons per secondary electron

Primary and secondary Light Measurements



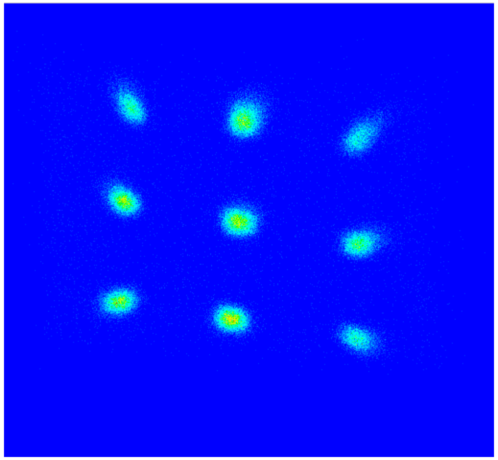


HT 1360V



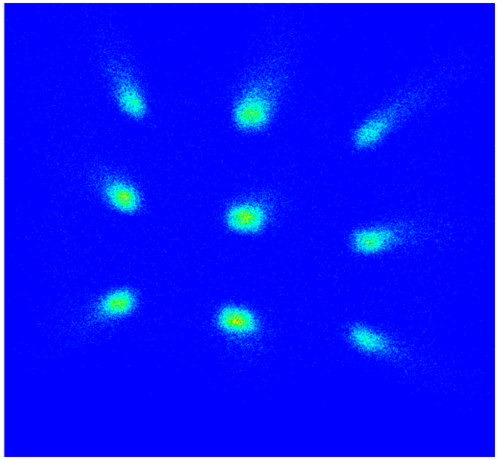
3 mm FWHM

1650V



1.6 mm

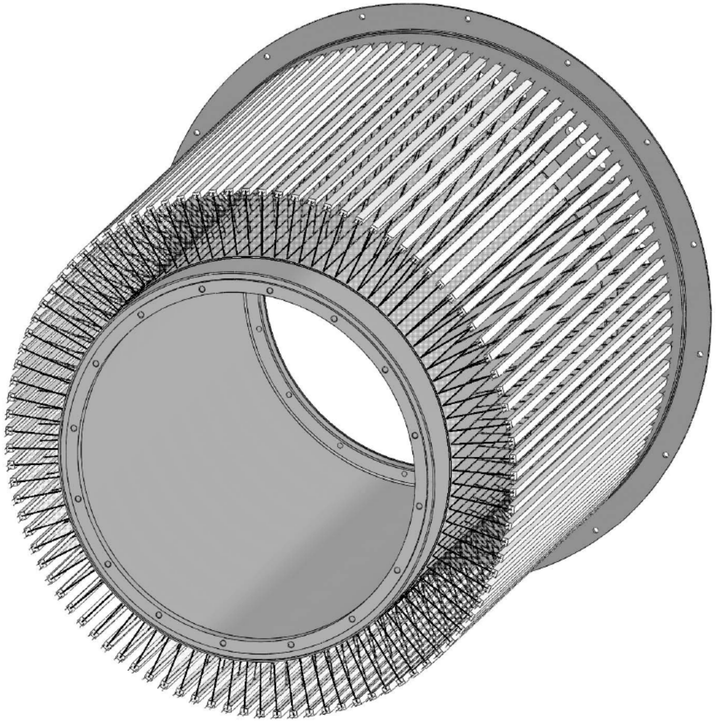
1850V

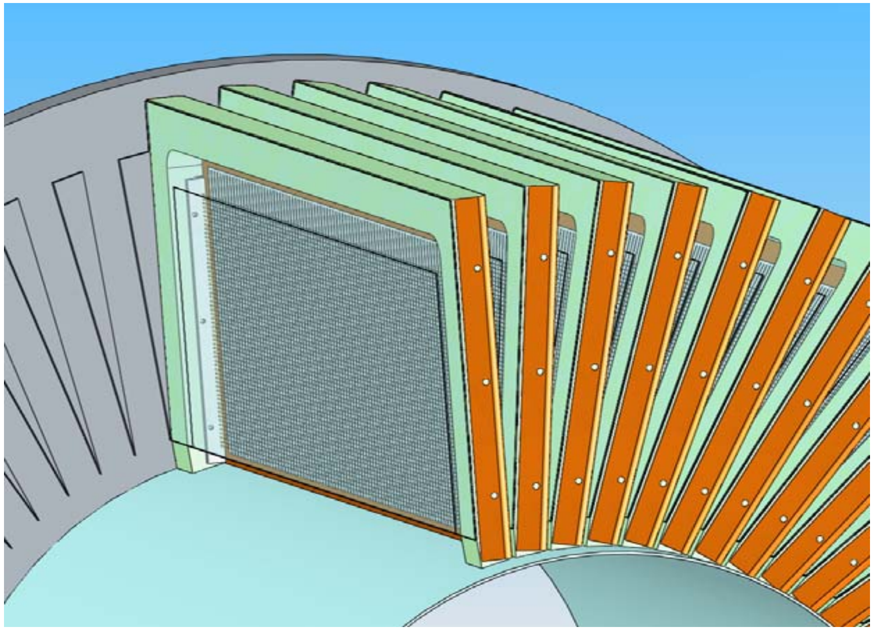


1.5 mm

ILL6C, 4 PMTs, square packing, 38mm diam.

Very large angular coverage → Study of the Multi-Blade gas detector



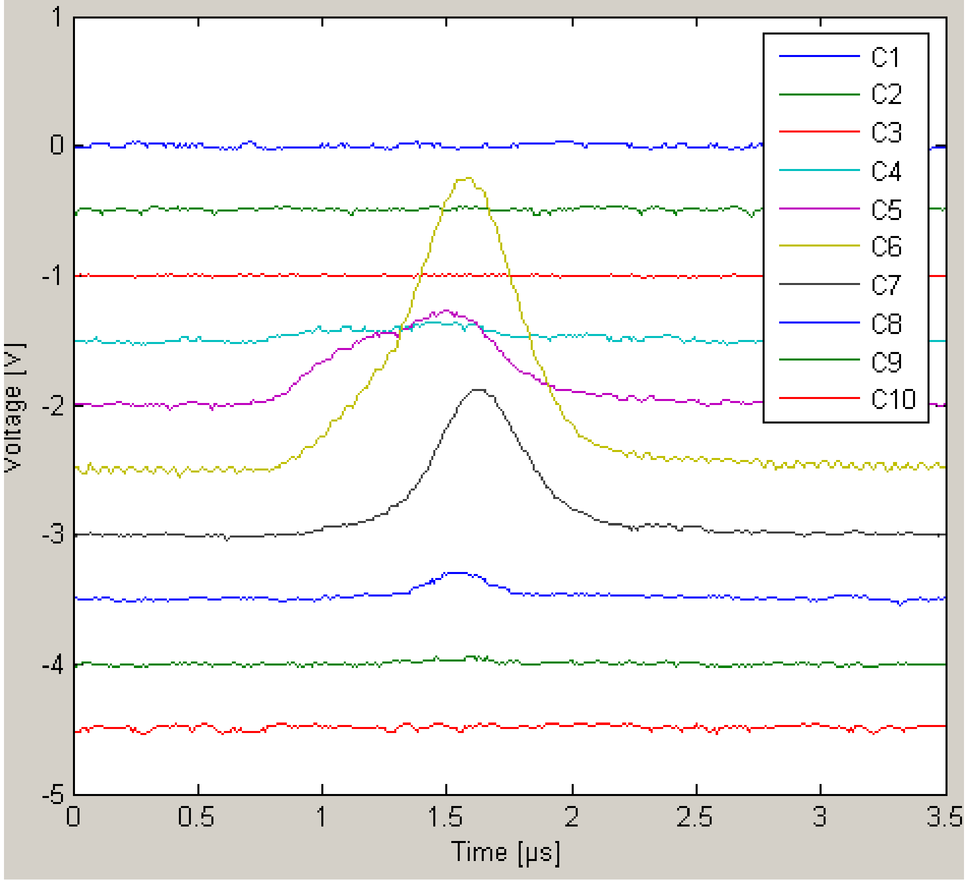


Each blade is made of an independent 2-dimensional MWPC flushed with Ar-CO2 at atmospheric pressure → low cost materials

Neutrons are converted on a ^{10}B-coated aluminium substrate oriented with a small angle to the incident neutrons → high efficiency + no parallax error + no dead zone

Tritium and Li tracks are processed by the electronics to detect the point of interaction → High resolution

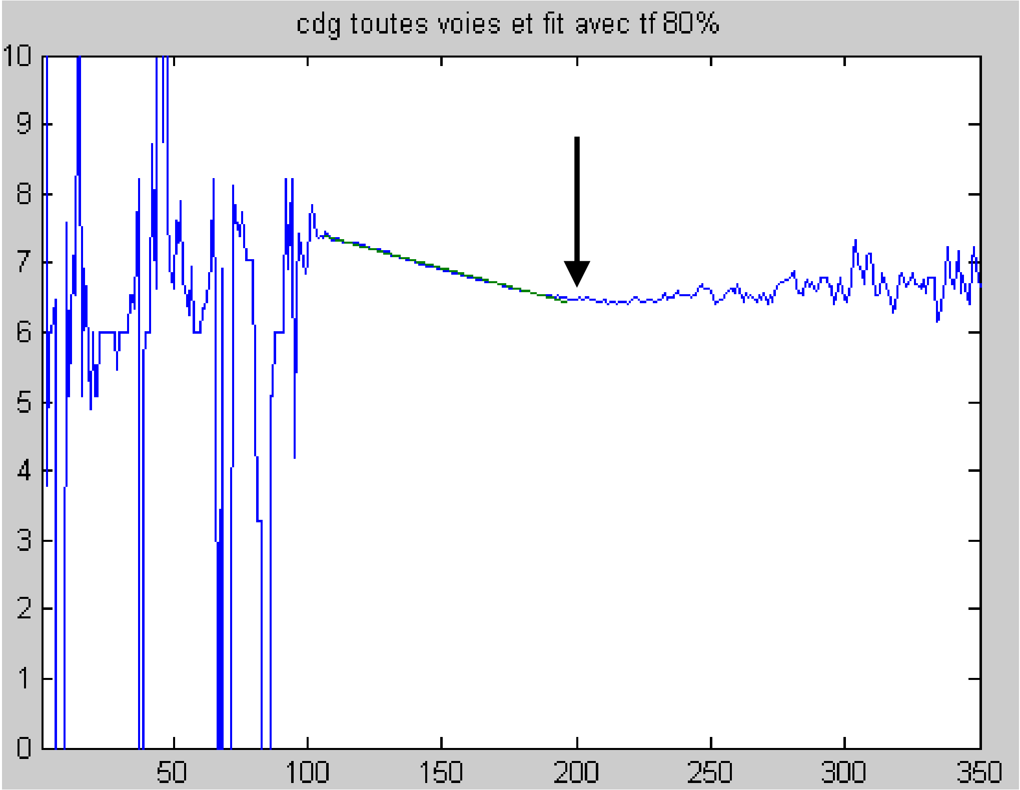
The multi-Blade gas detector



Signal measured on 10 wires in a ^{10}B-MWPC prototype equipped with an individual readout electronics
The pitch between wires is 2.5 mm.

The signal development reveals the orientation and the length of the ionizing track in the gas

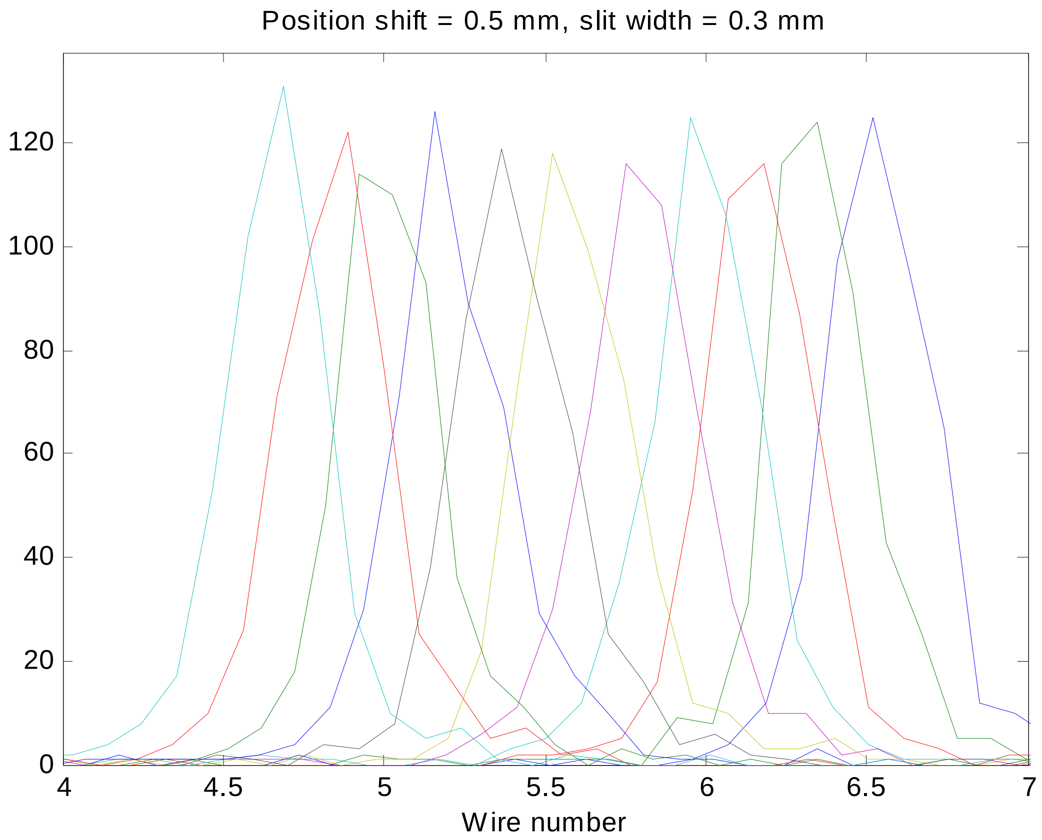
The multi-Blade gas detector



by calculating the centre of gravity of the signals on the 10 wires every 10 ns, we obtain the projection of the track trajectory on the axis Y perpendicular to the wires.

The horizontal section corresponds to the position of the capture point along Y.

The multi-Blade gas detector



Scanning along Y of the prototype with a collimated beam. The wire pitch is 2.5 mm. The distance shift between 2 successive beam positions is 0.5 mm. One colour corresponds to the position response of a Y bin of 0.5 mm width.

These distributions show that the spatial resolution obtained with the track processing is half that of the wire pitch.

CONCLUSION

Challenges for the future

- Sub-mm resolution and 3Pi sensitive area for SXD
- 1 mm and 10 MHz for Reflectometry
- Alternative to ^{3}He

some interesting candidates

→ Multiblade
→ MSGC-GSPC
→ ^{10}B + gas (Multiblade)

^{3}He is the unique gas usable today in neutron gas detectors; it has become recently very rare and expensive.
It is urgent to study alternatives

There are interesting work prospects in neutron detector development