Detectors for neutron scattering experiments

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Nomenclature

Category	Energy [meV]	Temperature [K]	λ [Å]
Ultra-cold	< 0.1	< 1	< 30
Cold	0.1 – 10	1 – 120	30 – 3
Thermal	10– 25-100	120 – 1000	3 – 1
Epithermal	> 500	> 6000	> 0.4
Fast	> ~ 10^5	> 10^6	>0.03

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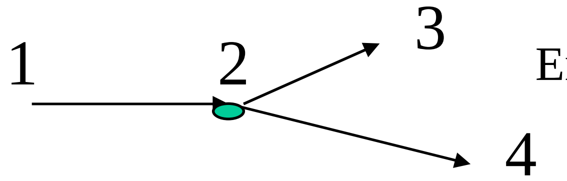
Schematics of nuclear reactions



Energy conservation $M_1+M_2+T_1= M_3+M_4+T_3+T_4$ **(1)**

1 **Elastic collision** (rest) mass and T_{kin} are conserved; $M_1=M_3$; $M_2=M_4$

2 **Anelastic collision*** mass is conserved, T_{kin} is not conserved

3 **Nuclear reactions** mass and T_{kin} are not conserved

$Q= (M_1+M_2) – (M_3+M_4)$ **(2) Q-value defintion**

•Condensed matter scientist use the term **anelastic** to mean reaction of type 1 when E_n initial $\neq E_n$ final (exchange of $E = \hbar\omega$ and $Q = \hbar q$)

Schematics of nuclear reactions

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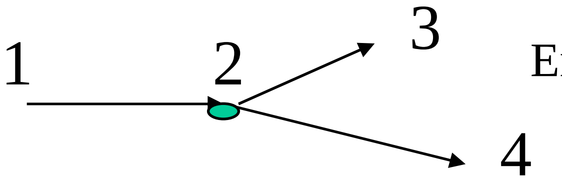

Energy conservation $M_1+M_2+T_1= M_3+M_4+T_3+T_4$ (1)

eq.1 + eq.2 $(T_3+T_4) - T_1= Q$

$M_1= M_3$, $M_2= M_4$ and $Q=0$ **Elastic reactions**

$M_1= M_3$, $M_2 \rightarrow M_4^*$ and $Q\neq0$ **Anelastic reactions**
(M_4 is left in an excited state)

$Q<0$ Endhotermic Mass is created from kinetic energy
$Q>0$ Esothermic Mass is trasnformed in kinetic energy

$M_1\neq M_3$ or $M_2\neq M_4$ and $Q\neq0$ **Nuclear reactions** ←
Used for detection of thermal neutrons

Reactions for slow neutron detection

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- n + ^{10}B **(a.i. 20%)** → ^{7}Li* + α → ^{7}Li + α + 0.48 MeV γ + 2.3 MeV (93%) 3840 barns
  → ^{7}Li + ^{4}He + 2.8 MeV (7%)
- n + ^{3}He → ^{3}H + ^{1}H + 0.764 MeV (expensive and scarce resource) **5330 barns**
- n + ^{6}Li (a.i. 7%)→ ^{4}He + ^{3}H + **4.79 MeV** **(resonance at 100keV)** 940 barns

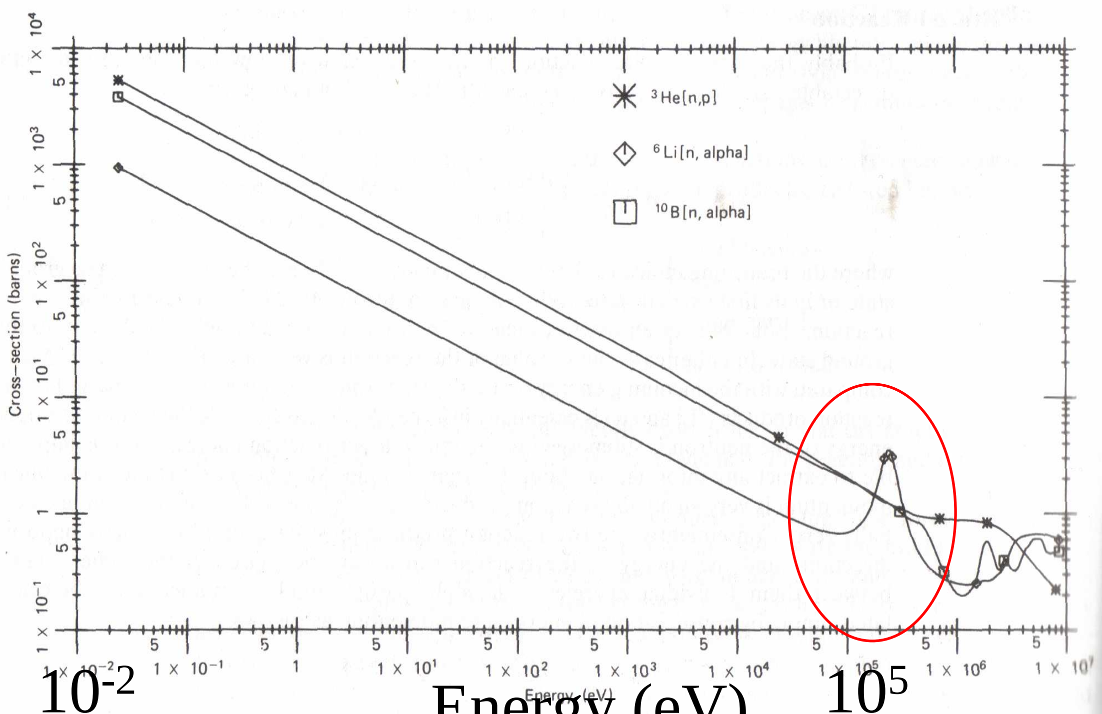
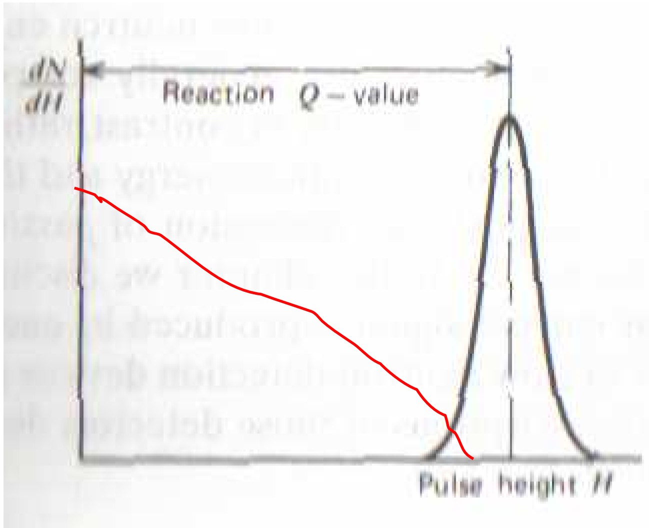


Figure 14.1 Cross section versus neutron energy for some reactions of interest in neutron detection.

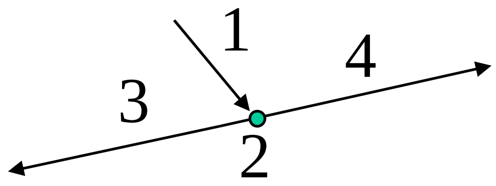
Detectors for slow neutrons

Ideal dector:
High detection efficiency (cross section)
Large Q values (only Q>0)
Stop reaction products
Immune to background (often γ rays)



$E_{kinetics}$ of the products=Q + ~~E_n~~=Q
Products emitted back-to-back (P_{init}~0) in the lab. ref. system

$$\begin{cases} E_3 + E_4 = Q \\ m_3 v_3 + m_4 v_4 = 0 \end{cases} \quad \ldots \quad E_{3,4} = \frac{m_{4,3}}{m_3 + m_4} \cdot Q$$



Scintillation Detectors

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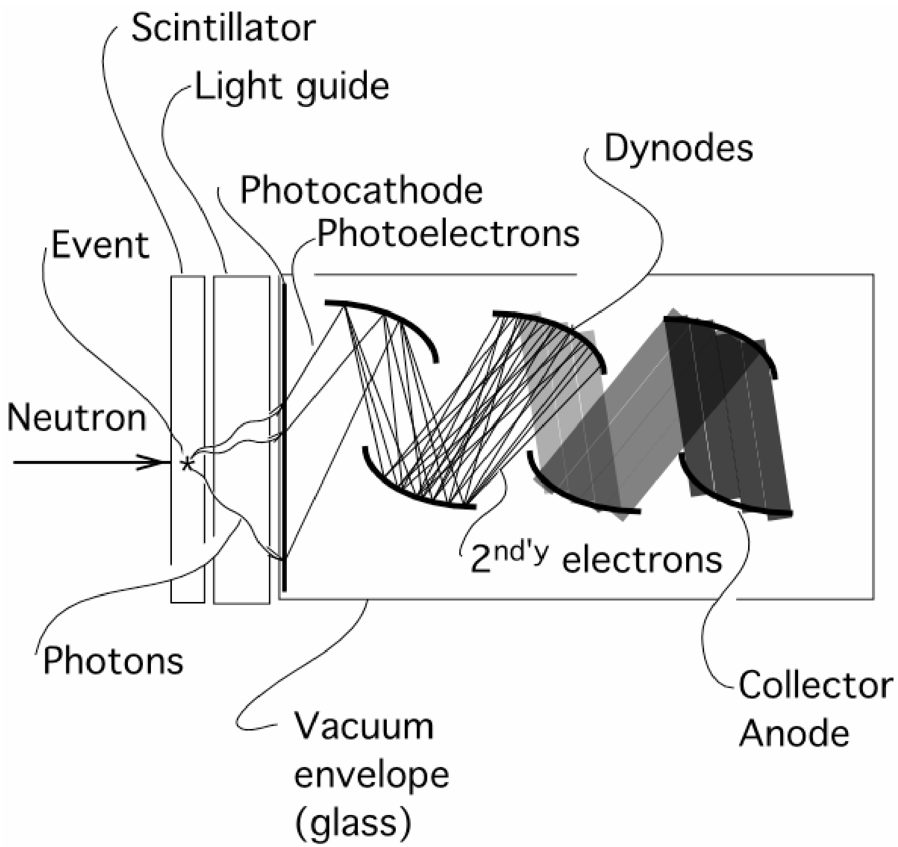

$$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.79\ MeV$$

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

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.

An efficient gamma ray detector with little sensitivity to neutrons, used in conjunction with neutron capture gamma-ray converters, is YAP (yttrium aluminum perovskite, $YAl_2O_3(Ce^{3+})$).

Some Common Scintillators for Neutron Detectors

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

GEM Detector Module (at ISIS)

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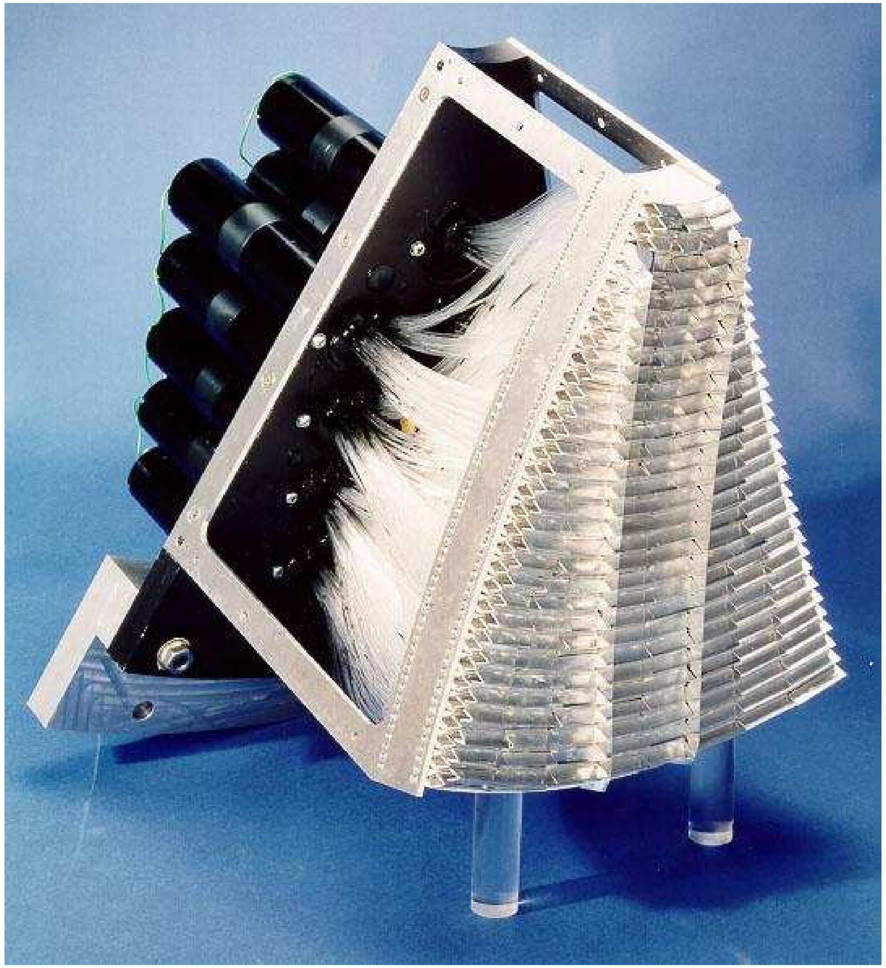

Hamamatsu Multicathode Photomultiplier

Compact photomultipliers are essential components of scintillation area detectors. The figure shows a recently developed multicathode photomultiplier, Hamamatsu model 8500.

256 ch Focusing Type   64 ch Focusing Type

Principle of Crossed-Fiber Position-Sensitive Scintillation Detector

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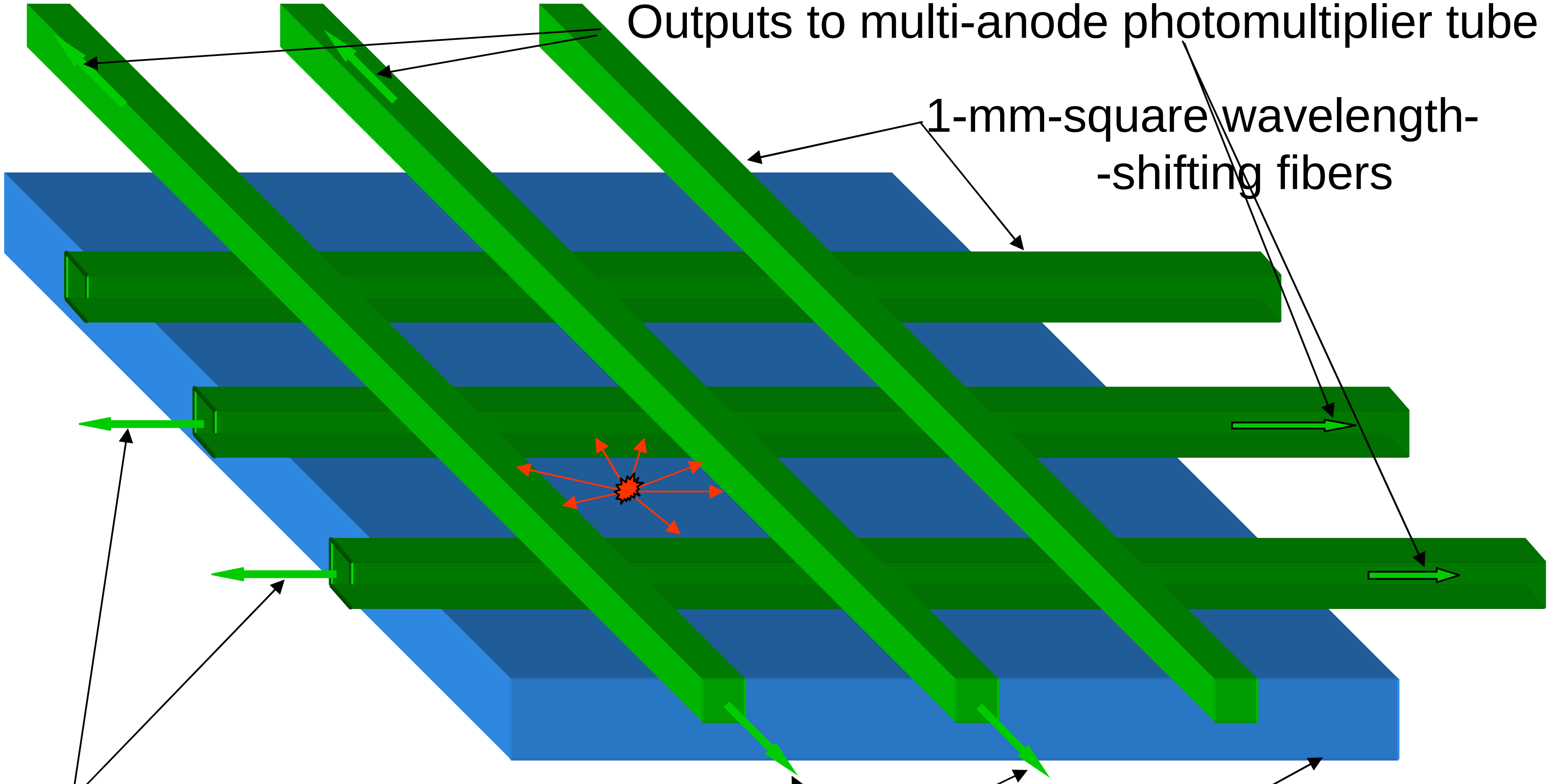

16-element WAND Prototype Schematic and Results

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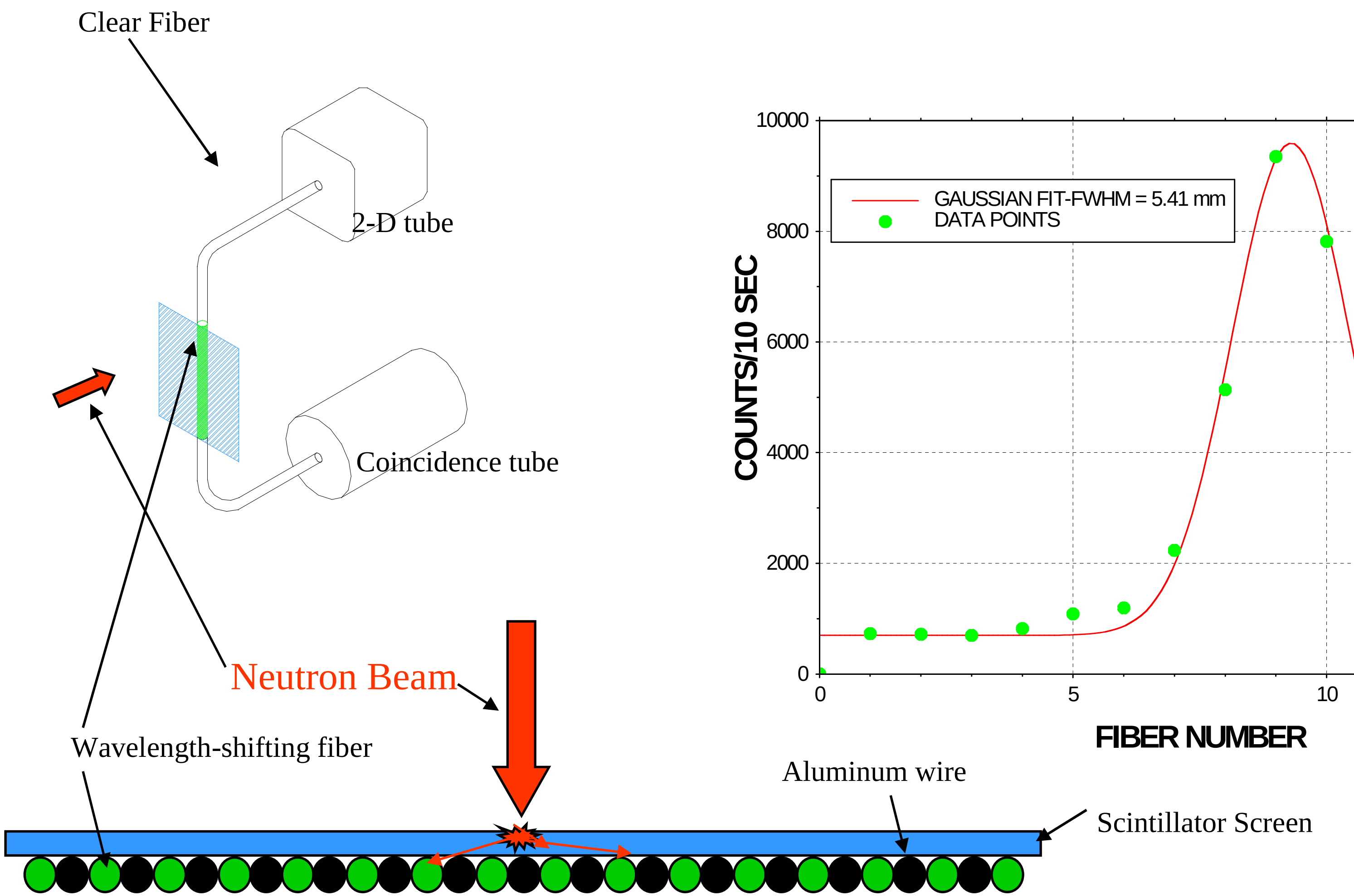

Crossed-Fiber Scintillation Detector Design Parameters (ORNL I&C)

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- 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.

SNS 2-D Scintillation Detector Module

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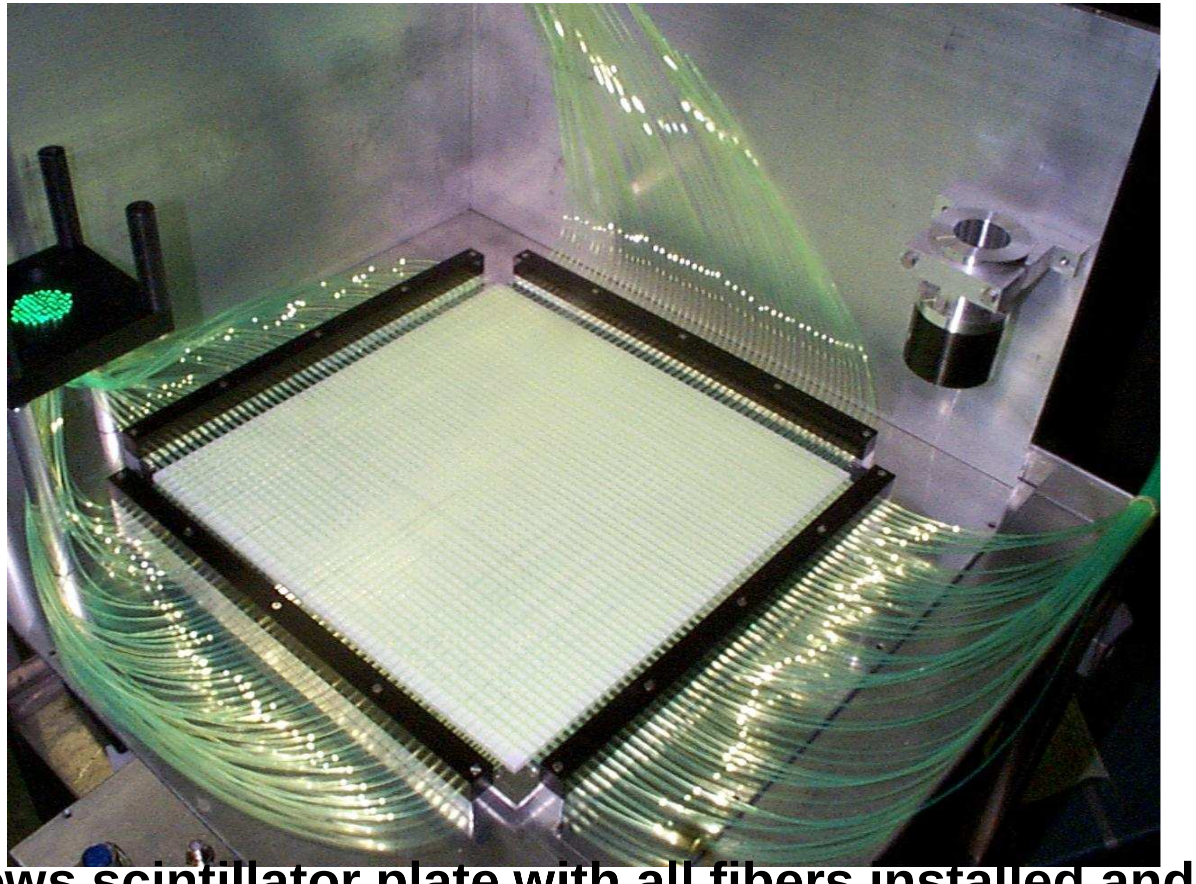

Shows scintillator plate with all fibers installed and connected to multi-anode photomultiplier mount.

Neutron Scattering from Germanium Crystal Using Crossed-Fiber Detector

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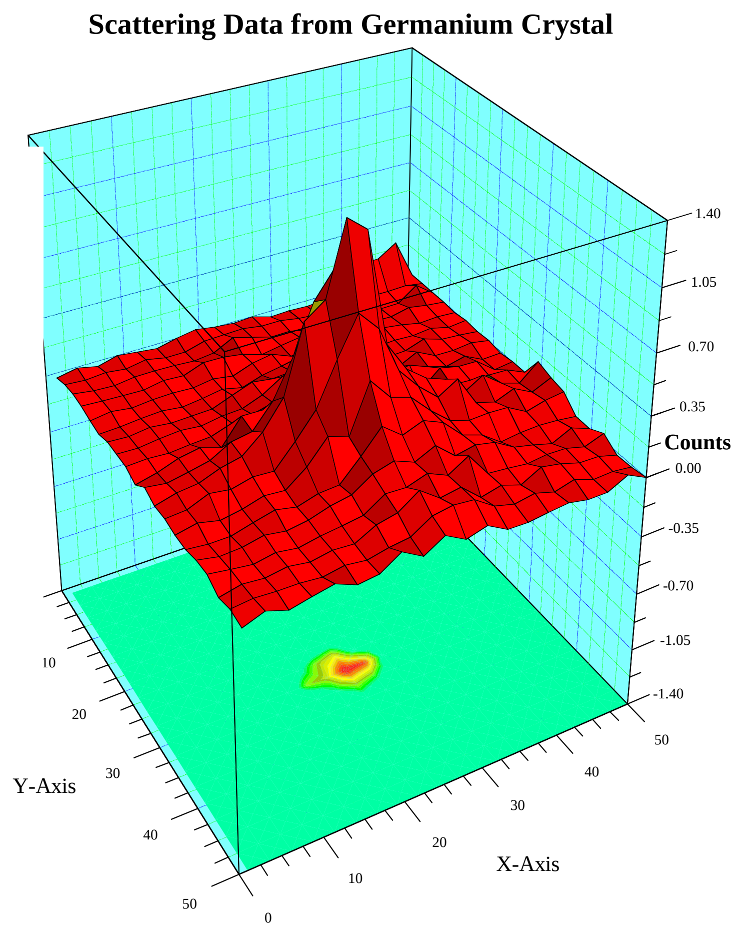
- Normalized scattering from 1-cm-high germanium crystal.
- $E_n \sim 0.056$ eV.
- Detector 50 cm from crystal.



Neutron Detector Screen Design

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The scintillator screen for this 2-D detector consists of a mixtureof ^{6}LiF and silver-activated ZnS powder in an optical grade epoxy binder. Neutrons incident on the screen react with the ^{6}Li to produce a triton and an alpha particle. These charged particles passing through the ZnS(Ag) cause it to emit light at a wavelength of approximately 450 nm. The 450-nm photons are absorbed in the wavelength-shifting fibers where they convert to 520-nm photons, some of which travel toward the ends of the fibers guided by critical internal reflection. The optimum mass ratio of ^{6}LiF:ZnS(Ag) is about 1:3.

The screen is made by mixing the powders with uncured epoxy and pouring the mix into a mold. The powder settles to the bottom of the mold before the binder cures. The clear epoxy above the settled powder mix is machined away. The mixture of 40 mg/cm^2 of ^{6}LiF and 120 mg/cm^2 of ZnS(Ag) used in this screen provides a measured neutron conversion efficiency of over 90% for 1.8 Å neutrons.

Spatial Resolution of Area Scintillation Detectors

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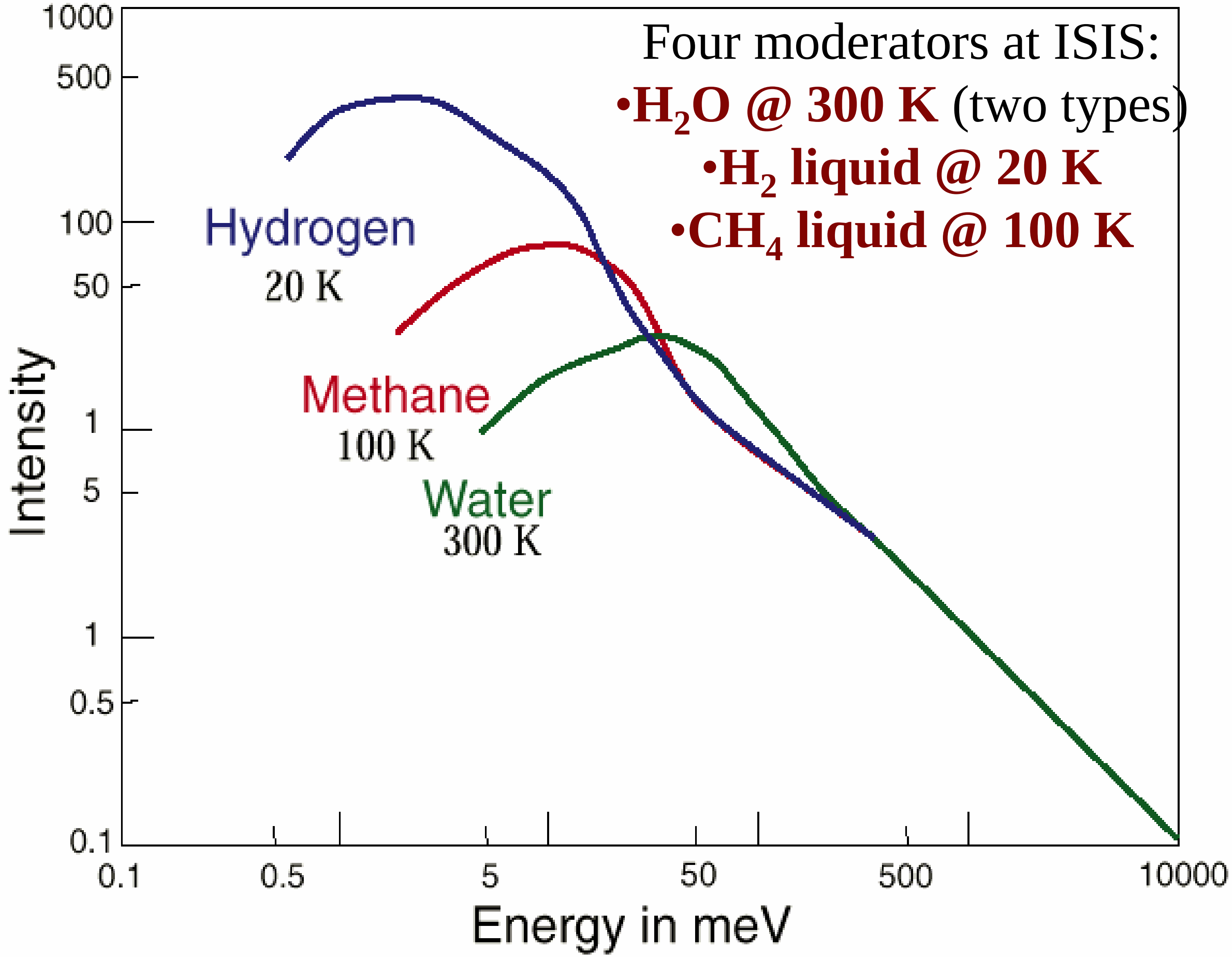
The spatial resolution accomplishable in SDs is typically better than in gas detectors. The range of neutrons is less. The range of ionizing particles is less in solid materials than in gases.

However, the localization of the light source (an optical process) imposes the limit on position resolution. This in turn depends statistically on the number of photons produced in the scintillator (more is better, of course).

Epithermal neutrons from spallation sources



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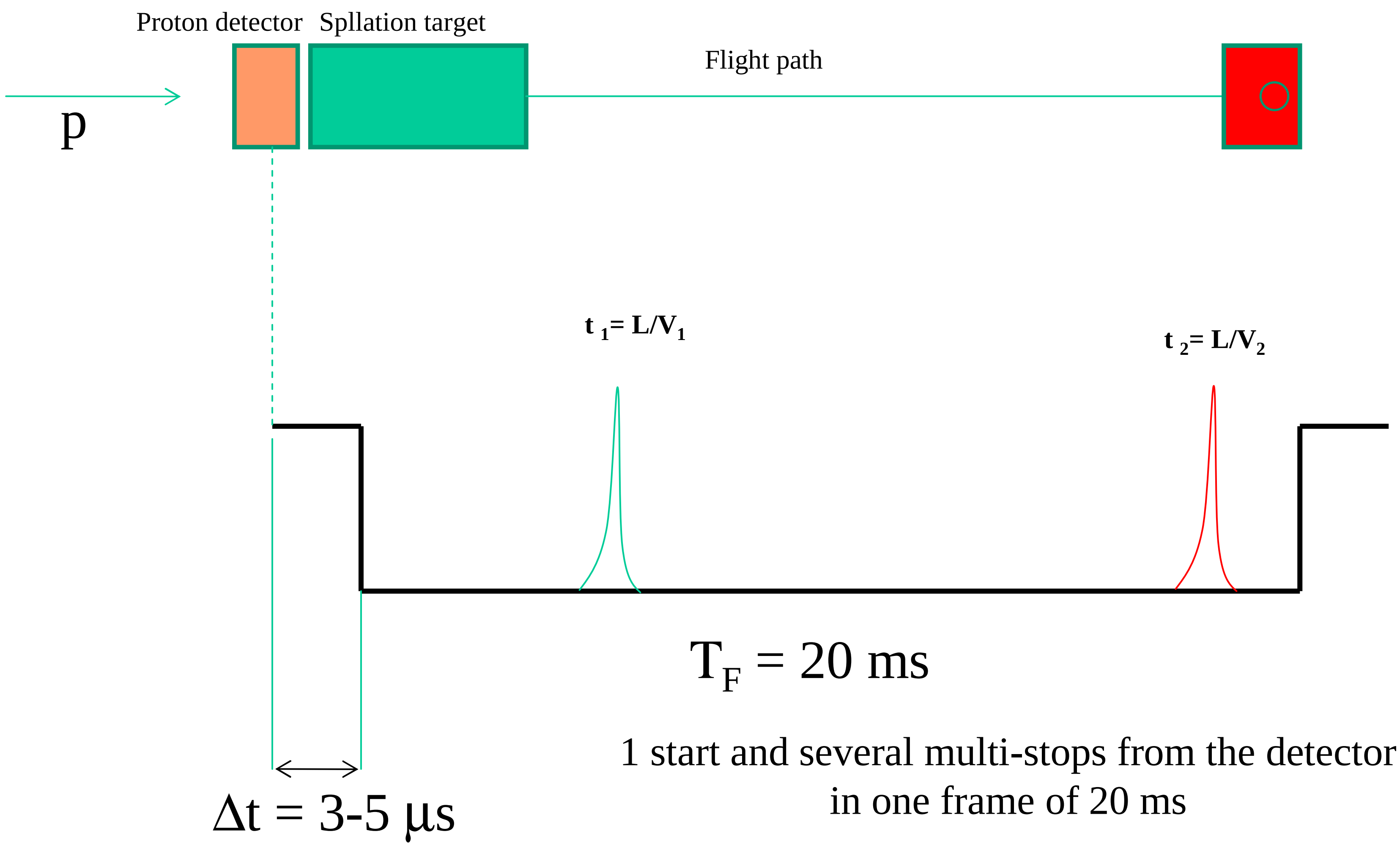
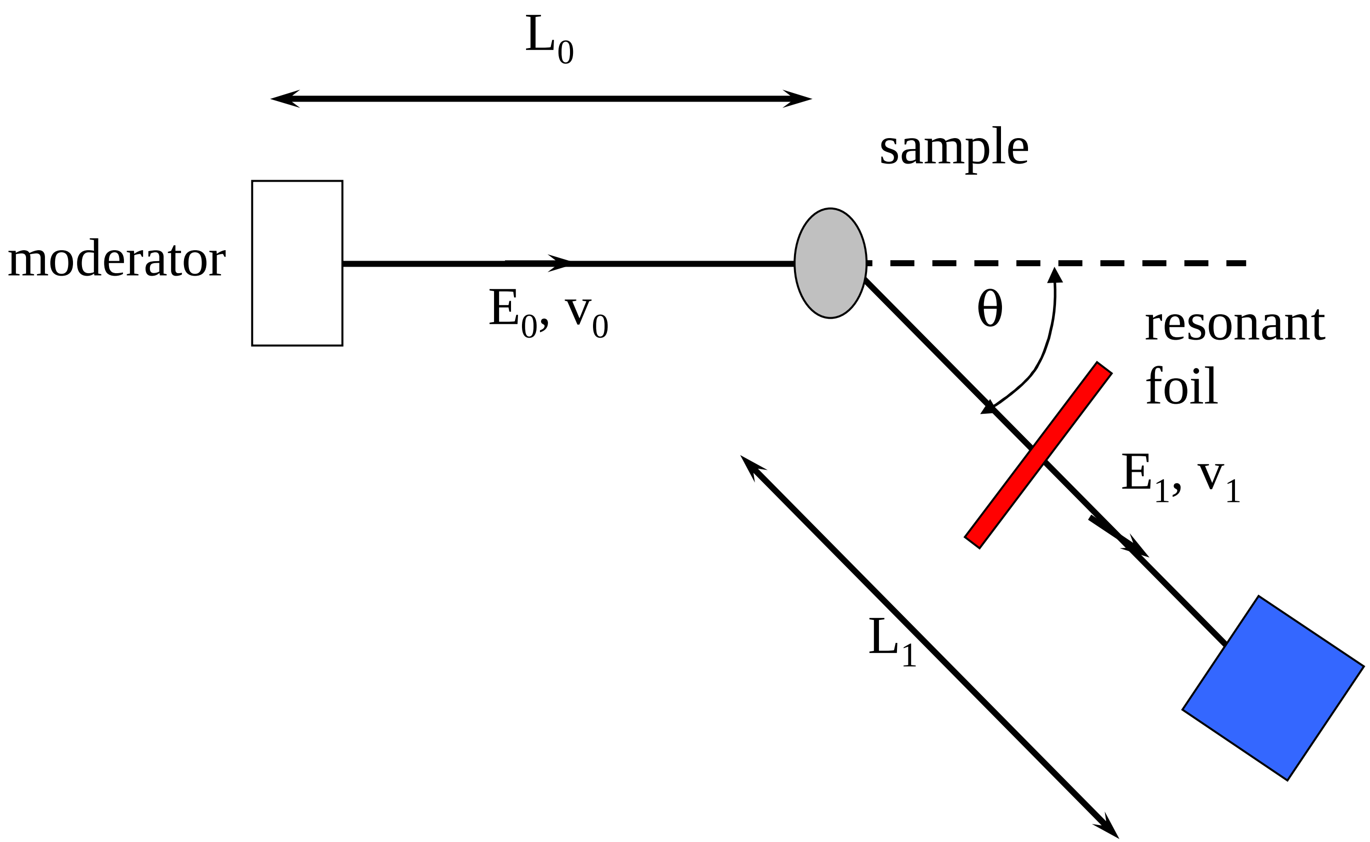
The Time of flight technique



1 start and several multi-stops from the detector in one frame of 20 ms

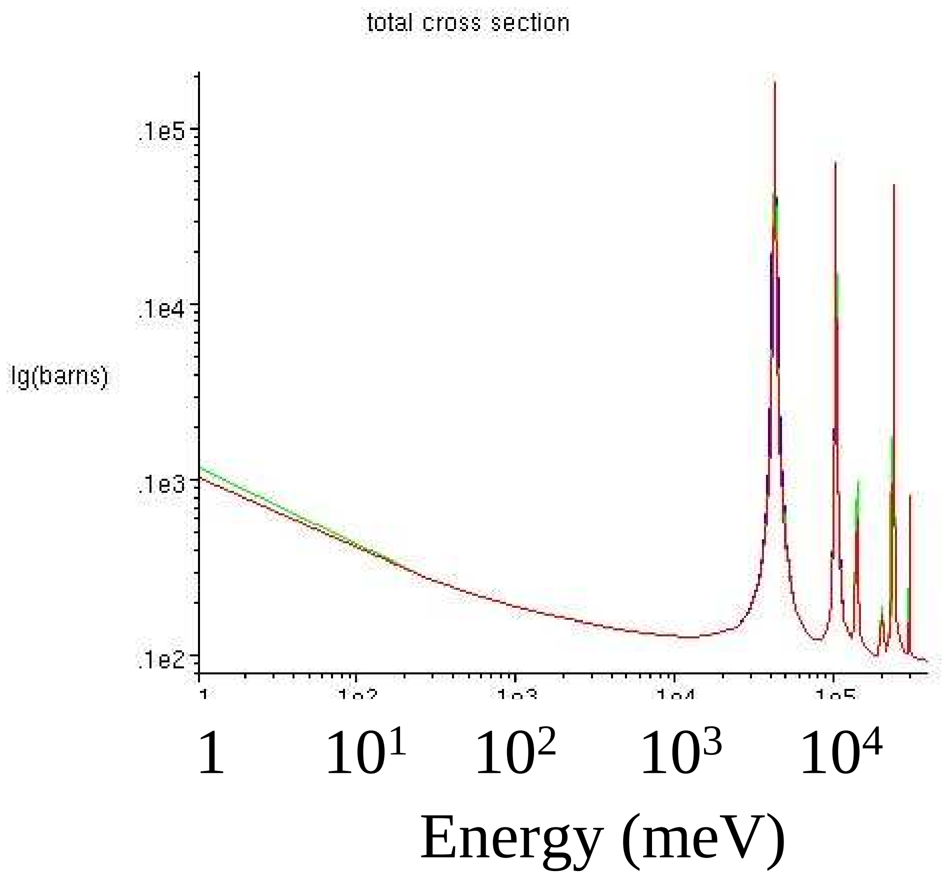
Time of flight neutron spectroscopy in inverted geometry



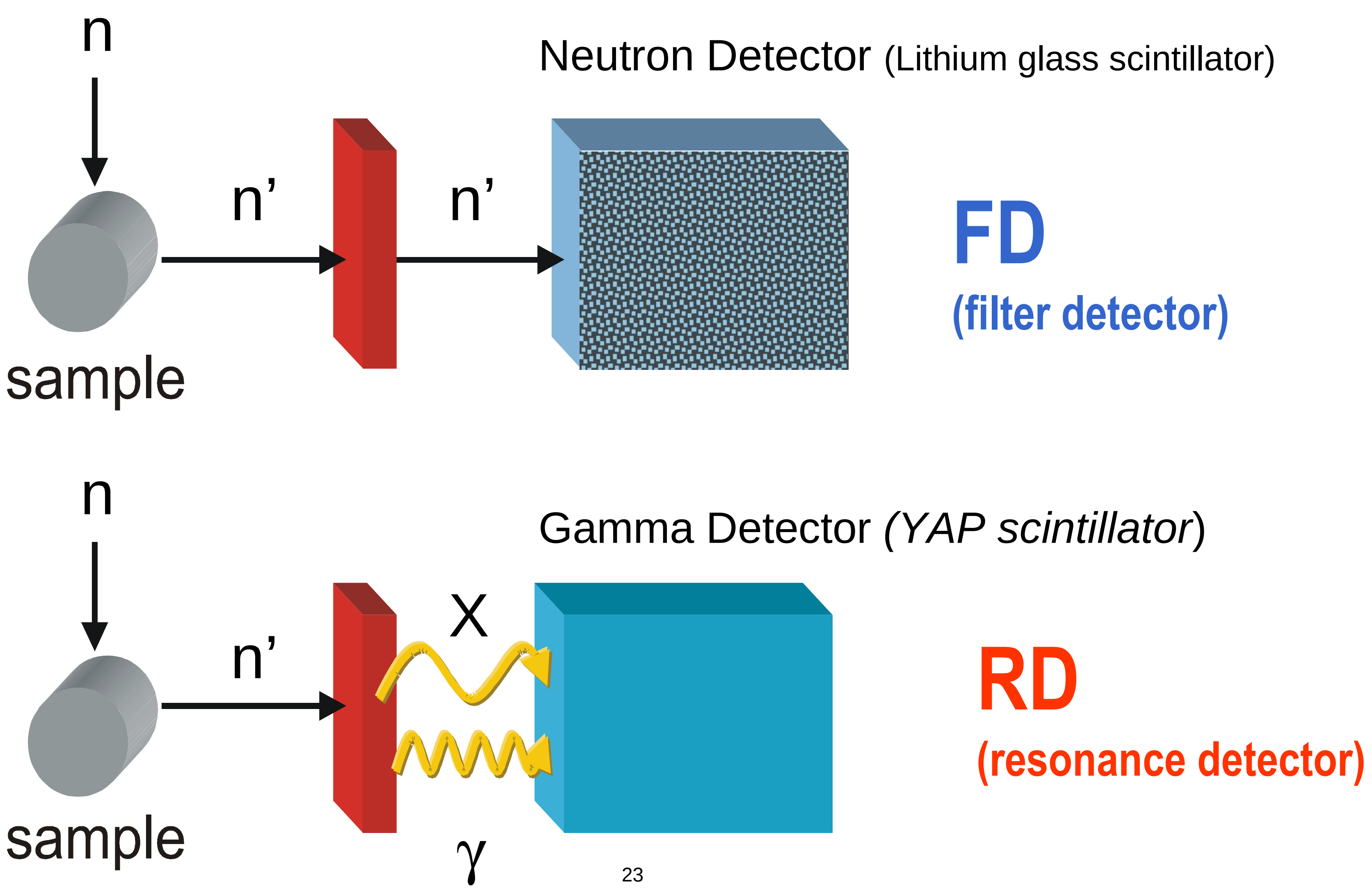
$$t = t_0 + \frac{L_0}{v_0} + \frac{L_1}{v_1}$$

Total Cross Section of Tantalum

Tantalum is essentially monoisotopic ^{181}Ta and is used as a neutron converter sensitive to energies near 4.28 eV.



Neutron detection techniques for epithermal neutrons



TOF spectra for FD (neutron detector) and RD (γ detector)

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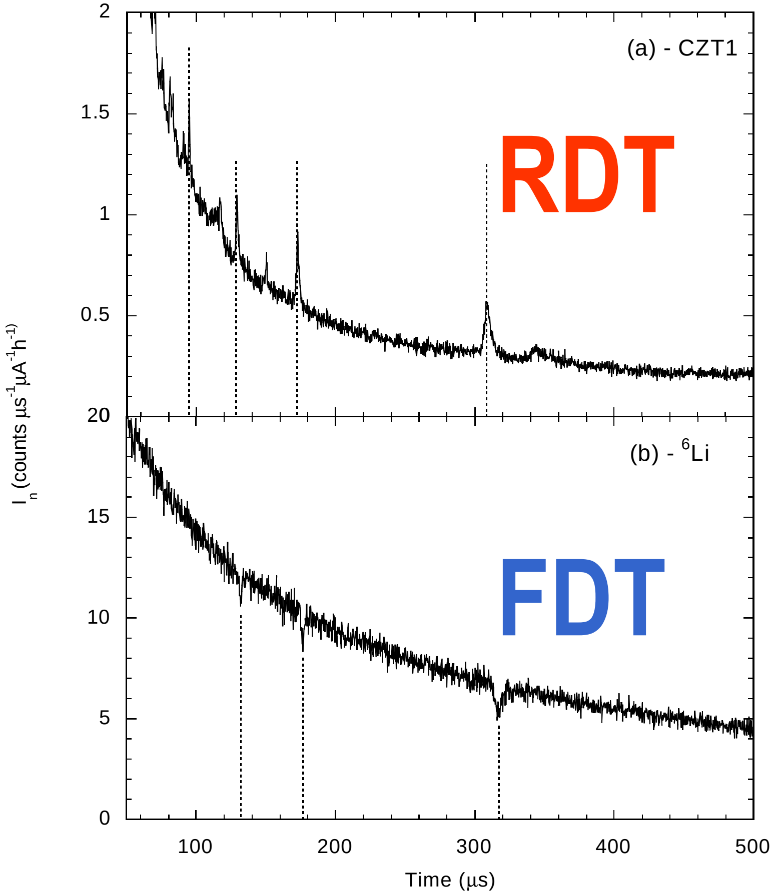

Pb sample
U foil

Resonance Detector principles

Two step process

i) Neutron absorption and conversion through **(n,γ) reaction**

ii) **Detection** of the emitted prompt gammas

RD properties

-The absorbing resonance fixes the final neutron energy

-Neutron conversion controls mainly the ***energy resolution*** **(ΔE/E)**

-Ability to detect gammas controls the ***signal to background ratio*** **(S/B)**

Advantages over Li-glass detectors

•no principle need for background subtraction

•no 1/v decrease of the detection efficiency:

i) detection efficiency not dependent on the neutron energy

ii) high efficiency for epithermal neutrons (10-100 eV)

Choice of the resonant element

Neutron absorbing resonance

$$\sigma(E) = \frac{\sigma_0}{1 + 4(E - E_0)^2 / \Gamma^2}$$

(Breit Wigner)

E_0 neutron resonance energy

σ_0 peak cross section (at $E=E_0$)

Γ (FWHM) intrinsic resonance width

Criteria for resonant elements

- Resonance energy: **E_0=10-100 eV**
- Isolated resonance (to avoid overlapping with other resonances)
- High cross section (high conversion efficiency) $\Rightarrow$ **$\sigma_0 = 10^4$-10^5 b**

•Narrow resonance (low ΔE/E)

⇒ **Γ~ 100 meV**

⇒ **Δ~ 100 meV** (Thermal Doppler broadening)

•Foil thickness

Compromise between neutron absorption probability, $P(E_n)$, and ΔE/E

$$P(E_n) = 1 - \exp(-N_d \cdot \sigma) \qquad N_d = \rho \cdot t$$

⇒ $\mathbf{N_d \cdot \sigma_0 = 1}$

•High yield of low energy gammas (10-300 keV) ⇒ choice of suitable detector

<u>Other desiderable features:</u> *high isotopic abundance, exist as metallic or oxide, low gamma self-absorption*

Best Isotopes

	i.a. (%)	density (g/cm^3)	E_0 (eV)	σ_0 (barn)	Γ (meV)	Δ (T=295 K) (meV)	Δ (T=75 K) (meV)
$^{139}La_{57}$	99.9	6.1	72.2	5969	96.0	231	125
$^{150}Sm_{62}$	7.4	7.4	20.7	56207	109.0	119	66
$^{238}U_{92}$	99.3	18.9	6.7	23564	25.0	54	31
	"	"	20.9	37966	34.0	96	55
	"	"	36.7	42228	57.0	127	73
	"	"	66.0	20134	48.0	170	98

Gamma yield (absolute) exists for thermal neutron capture, but incomplete database for resonant neutron capture

$^{139}La_{57}$ 218 keV 9 % **$^{238}U_{92}$** 12 keV
32 %
288 keV 9 % 48 keV
13 %
60 keV
12 %
$^{150}Sm_{62}$ 65 keV 30 % 134 keV
94 % 105 keV 9 % 4060 keV 7 %

Energy and relative intensities of γ-rays

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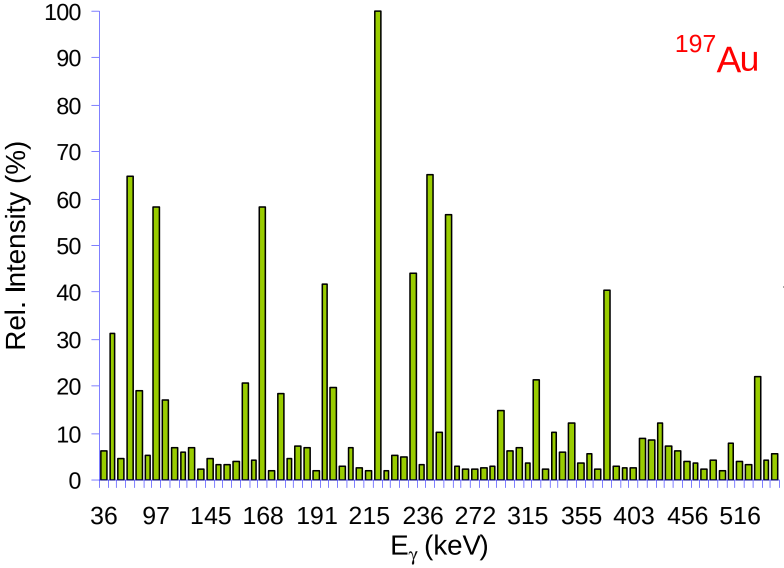

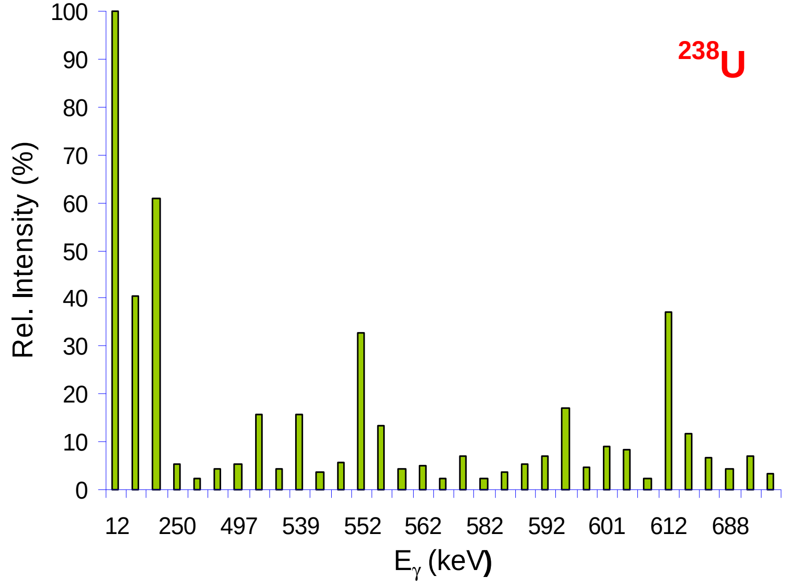

Suitable γ detectors for the RDS

Scintillators

1) NaI(Tl): good efficiency and energy resolution for MeV gamam ray. High sensitiviy to neutron backgorund (need of shielding).
2) **YAP**: good efficieny and moderate energy resolution. Low sensitivity to neutron background

Solid Sate

1) HpGe: excellente energy resoltuion, adequate efficienct . Radiation damange. Need to operate at cold temperature (77k)
2) Silicum: good for x-ray and low energy γ ray. Requires some cooling. Radiation damage
3) CdZnTe (CZT): Good efficiency and high energy resolution. Operate at room temperare. Small areas.

YAP detector

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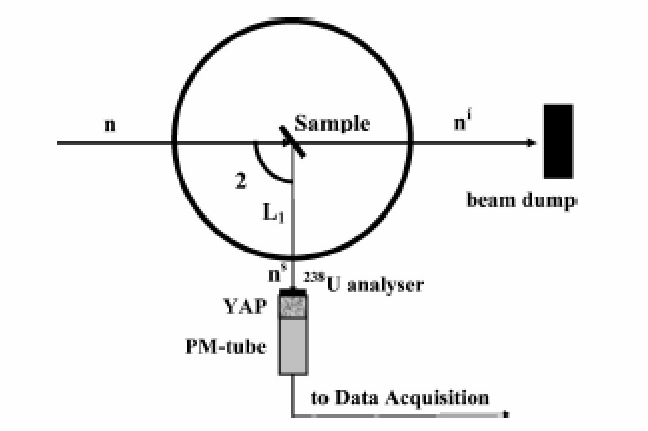
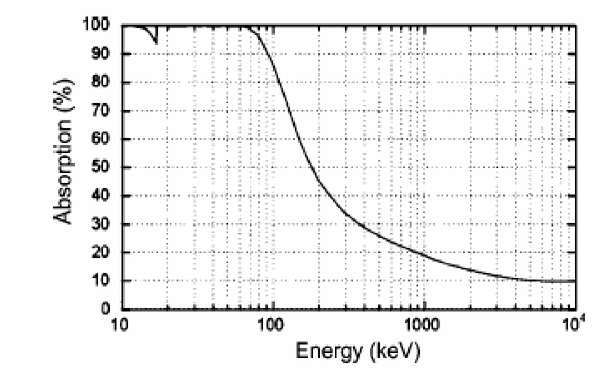
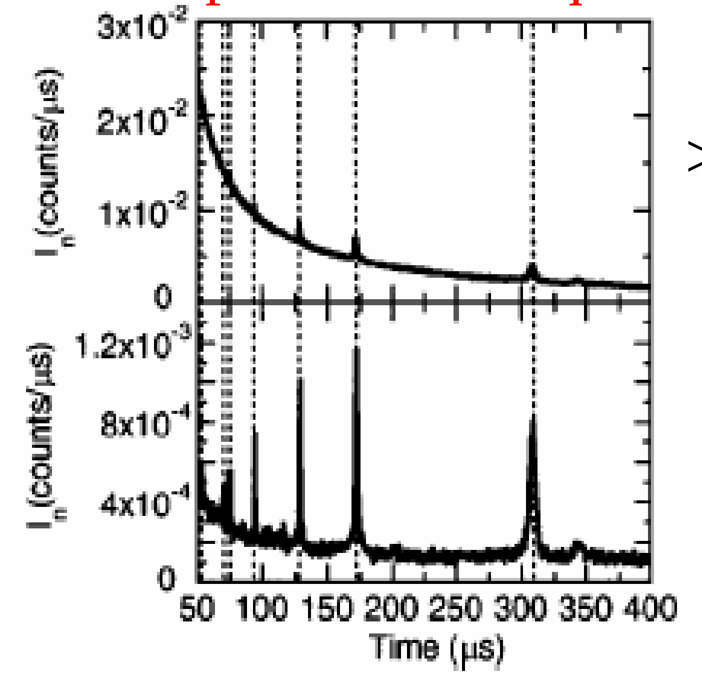




6mm thick

Biparametric acquisition



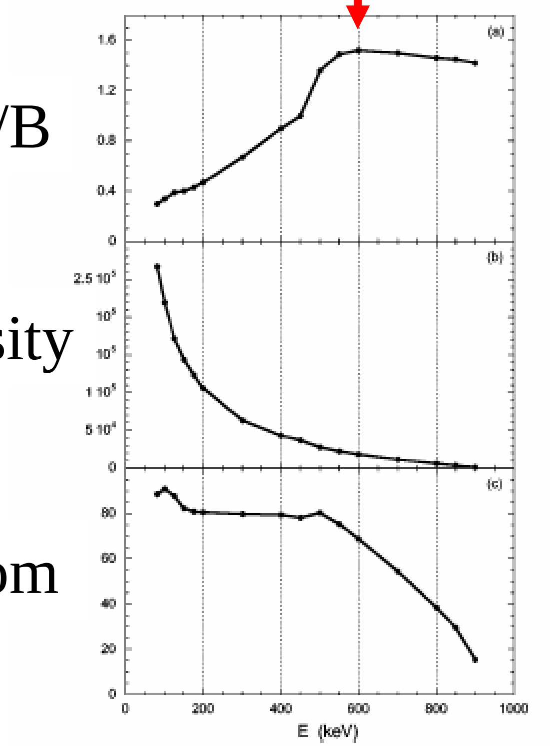
>40keV

>600keV

S/B

Intensity

fom



Fast neutrons

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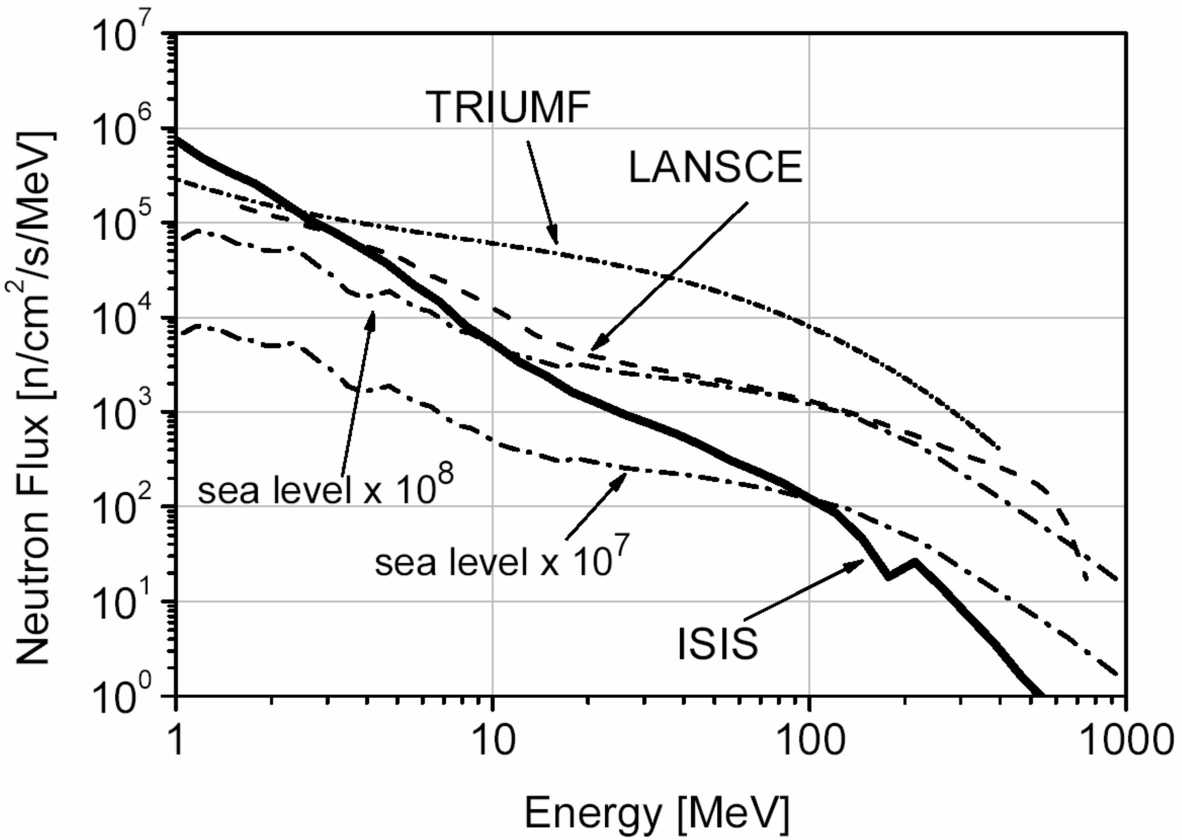
Fast neutron flux of VESUVIO at ISIS



Measured with activation targets

Enormous energy range 1-800 MeV!

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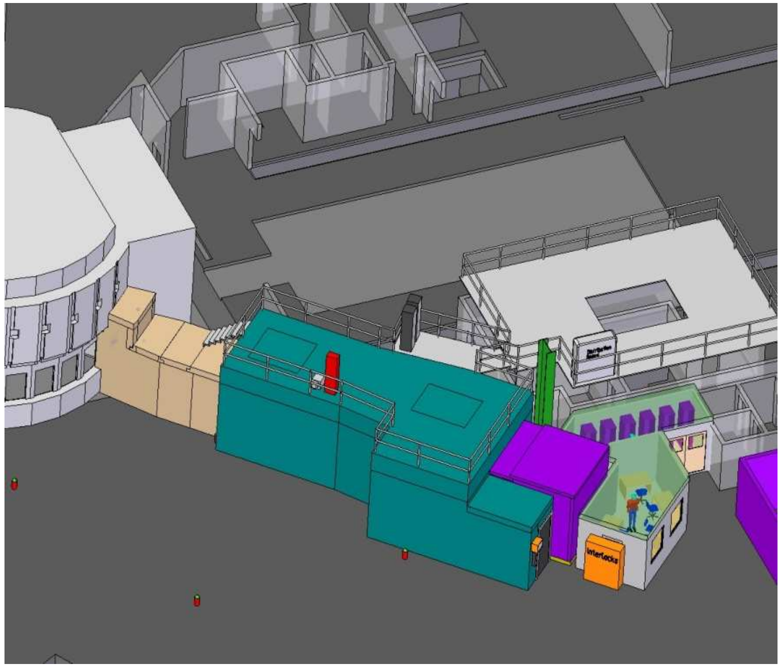
CHIPIR beam line at ISIS



Beam line dedicated to samples with dimension from a single chip to an entire electronic system.

$\Phi \approx 10^6$ n/cm²/s above 10 MeV

One hour on CHIPIR will be equivalent to 114 years on a plane

Need for beam monitor of the fast neutrons for the flux measurements

Fast neutrons detection

·Spherical dosimeters

•Scintillators

• ^{3}He proportional counters

•Proton Recoil Telescope (spectroscopy)

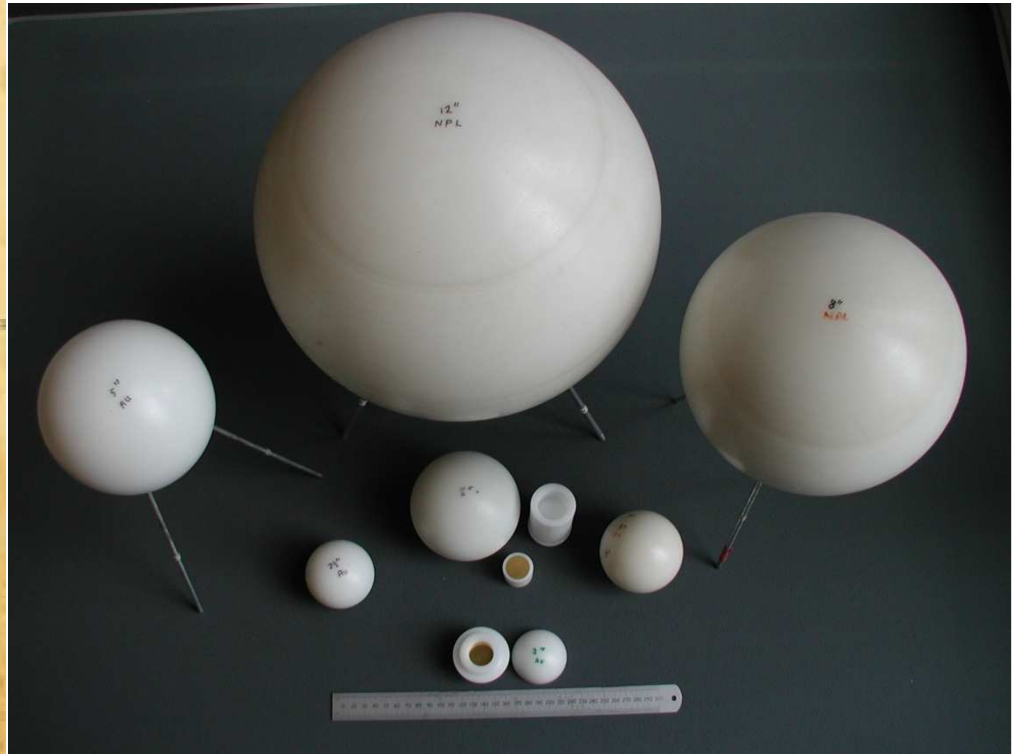
•Activation threshold targets

•TFBC

•Bonner Sphere

•Diamond detectors

•nGEM detector



Principle of operation

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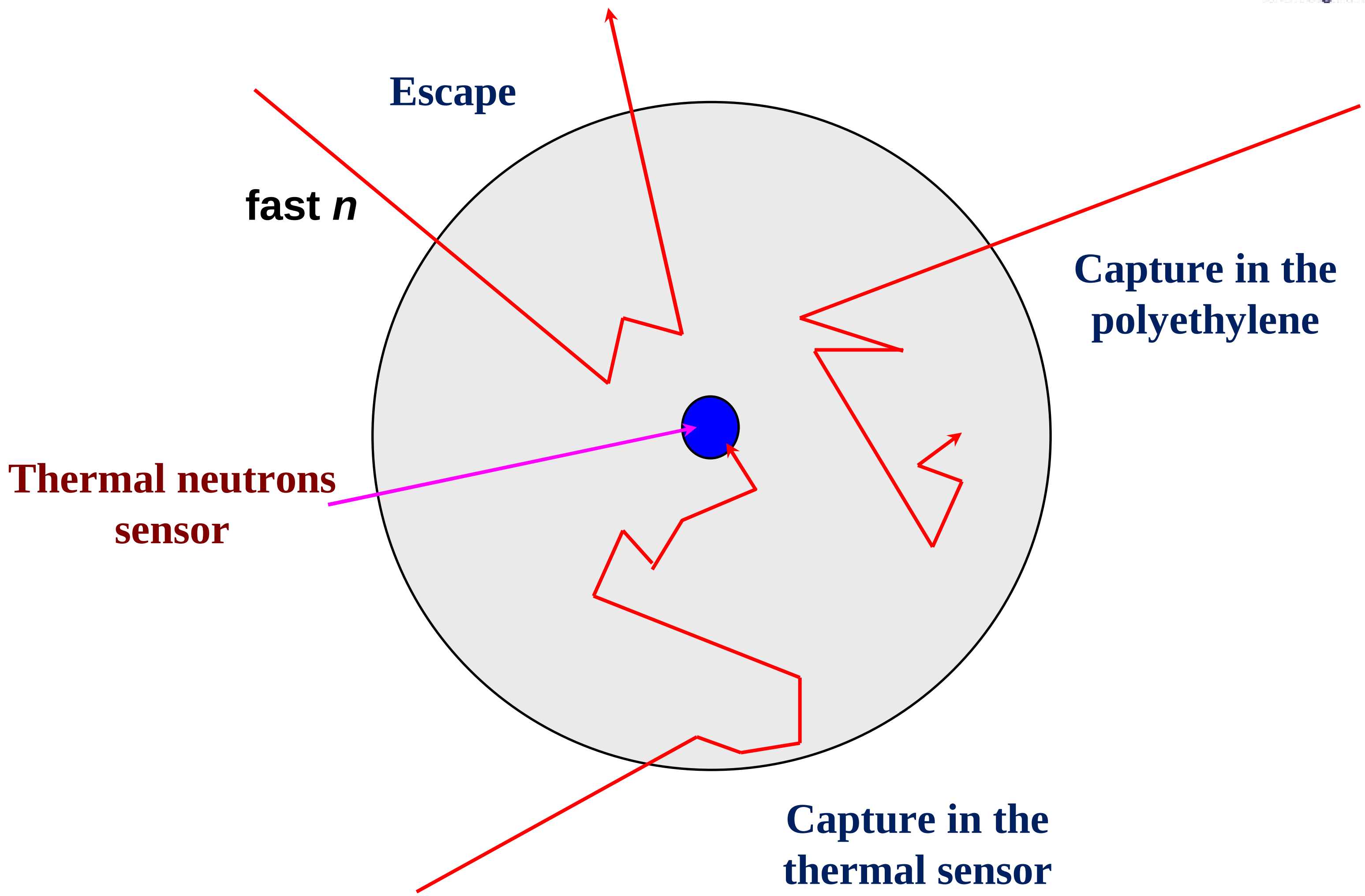

From the measured activity on the sensor after a period of irradiation the neutron flux at the selected energy range is found

Response Functions of Bonner Spheres

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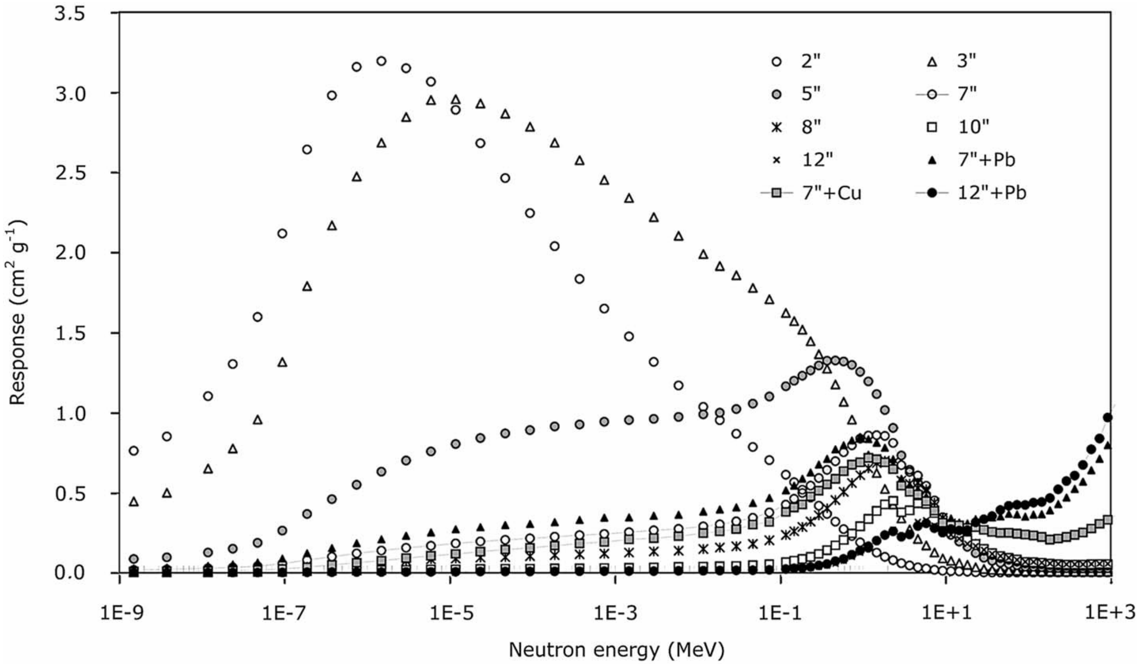

The very broad response function means that complicated deconvolution codes are needed to infer the incoming neutron spectrum from the mesaurement.

Diamond Detector

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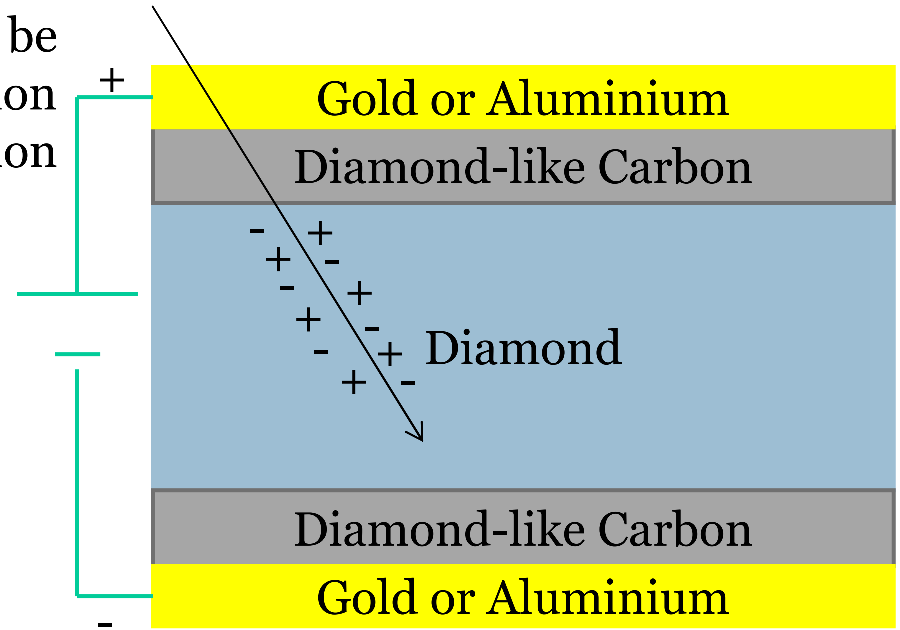
- Radiation hardness.
- High mobility of free charges (→fast response, comparable to Si, Ge).
- Room temperature operation (E_g=5.5 eV)→ No Cooling.
- Compact volume solid state detector.

With the CVD technique diamonds can be produced with good energy resolution (<1%) and 100% charge collection efficiency.

A charged particle passes through the diamond and ionizes it, generating electron–hole pairs (E_{e-h}=13 eV)



Carbon cross section

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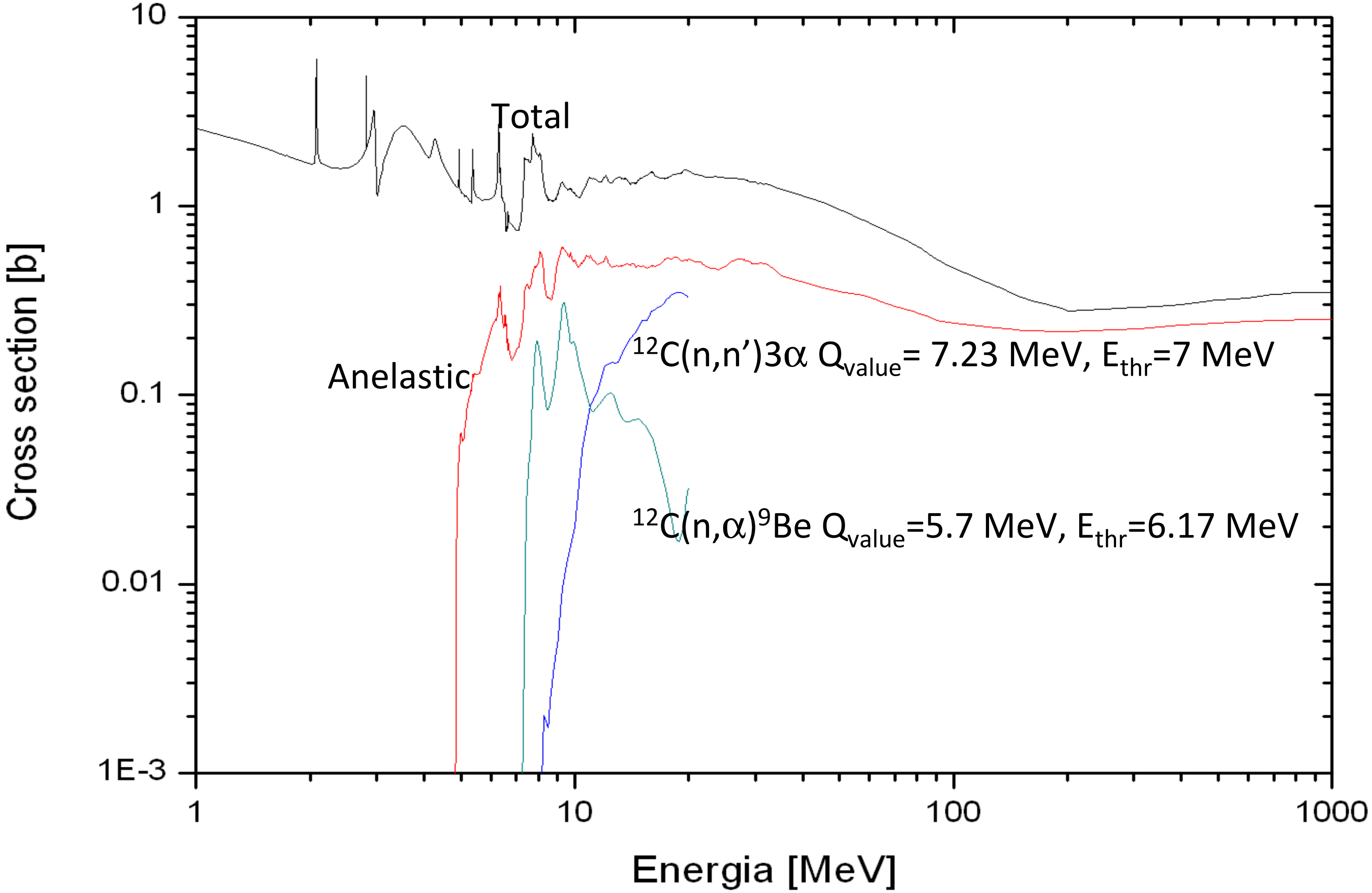

→ Fast neutron detection is achieved by detecting charge particles produced via the reactions:

- $^{12}C(n,\alpha)^{9}Be$
- $^{12}C(n,n')3\alpha$
- $^{12}C(n, n')^{12}C^{*}$

ıttering

Single-crystal Diamond Detector

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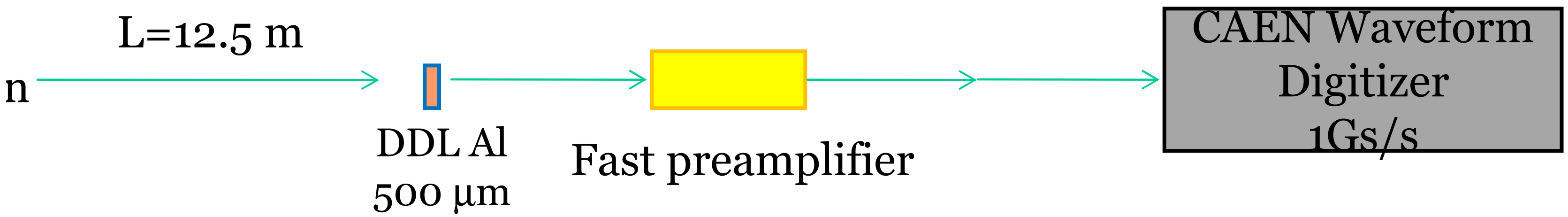

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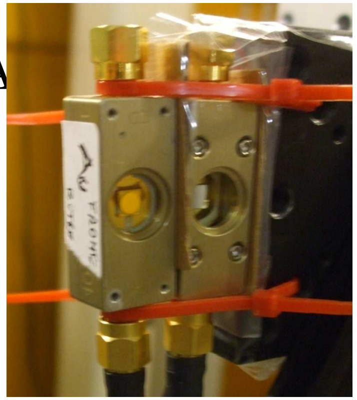
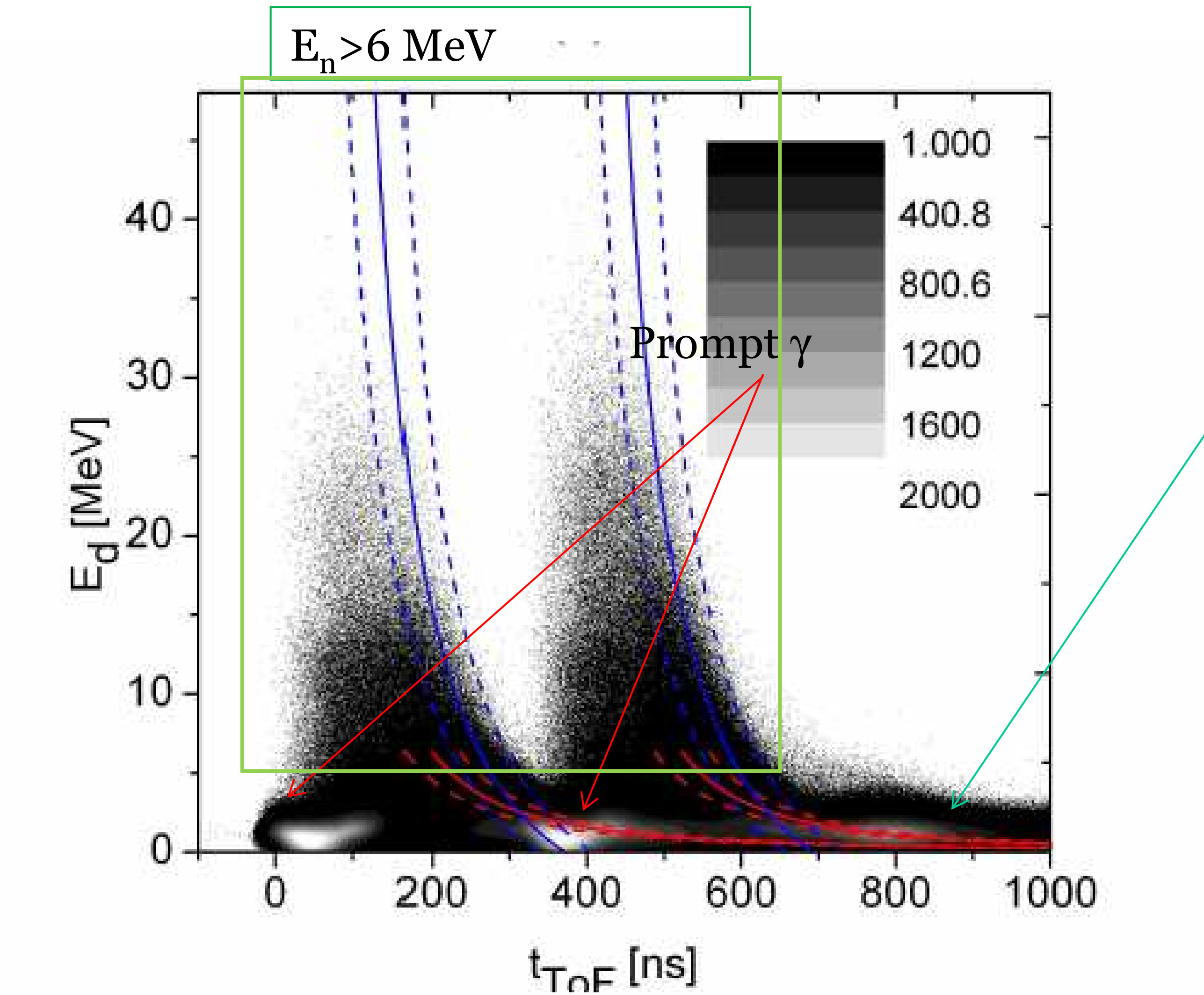


4x4x0.5 mm^3 sCVD
Al or Au contacts

	Si	Ge	CVD-Diamond
Atomic Number Z	14	32	6
Density [g/cm^3]	2.33	5.33	5.47
Band Gap [eV]	1.1	0.6	5.5
Electron Mobility [cm^2/V · s]	1350	3900	1800
Hole Mobility [cm^2/V · s]	480	1900	1200
Breakdown field [MV/cm]	0.3	0.1	10

Contour plot



Events due to the interaction of 3.5 MeV neutron which release energy via elastic recoil on the ^{12}C nucleus.

ToF spectra for high E_{dep} events

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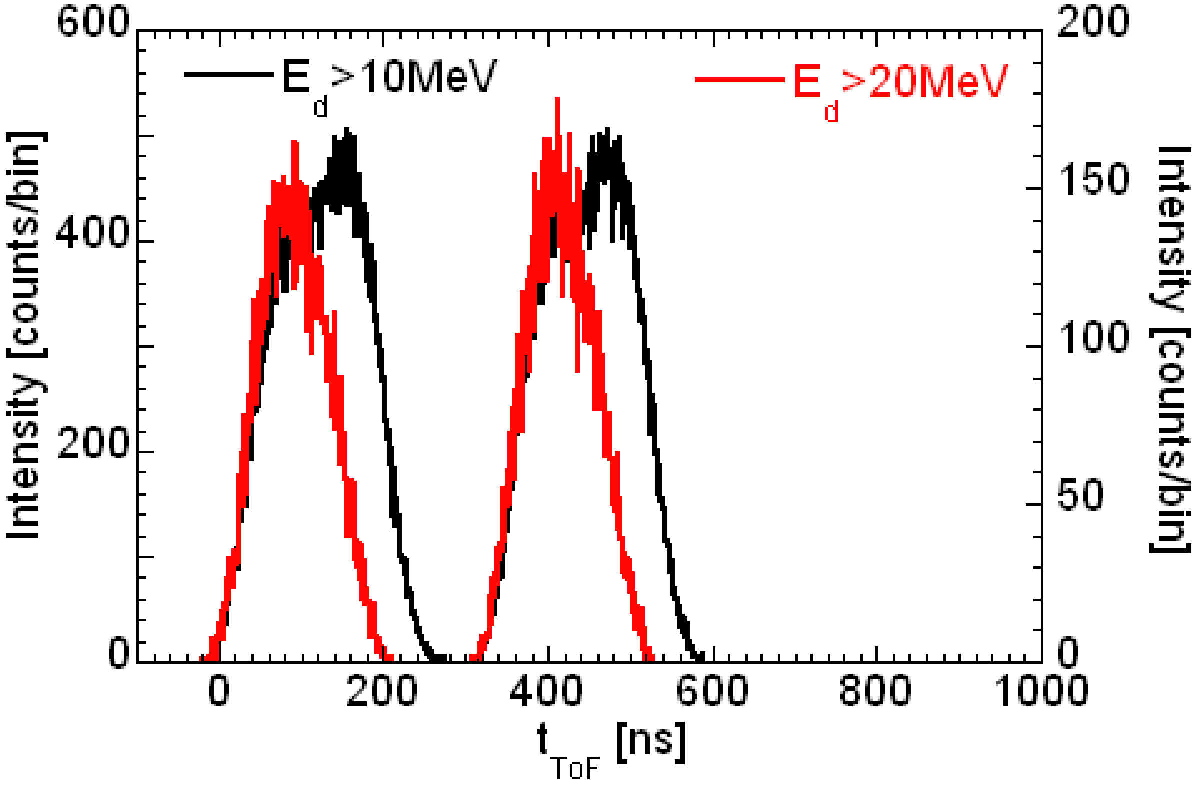


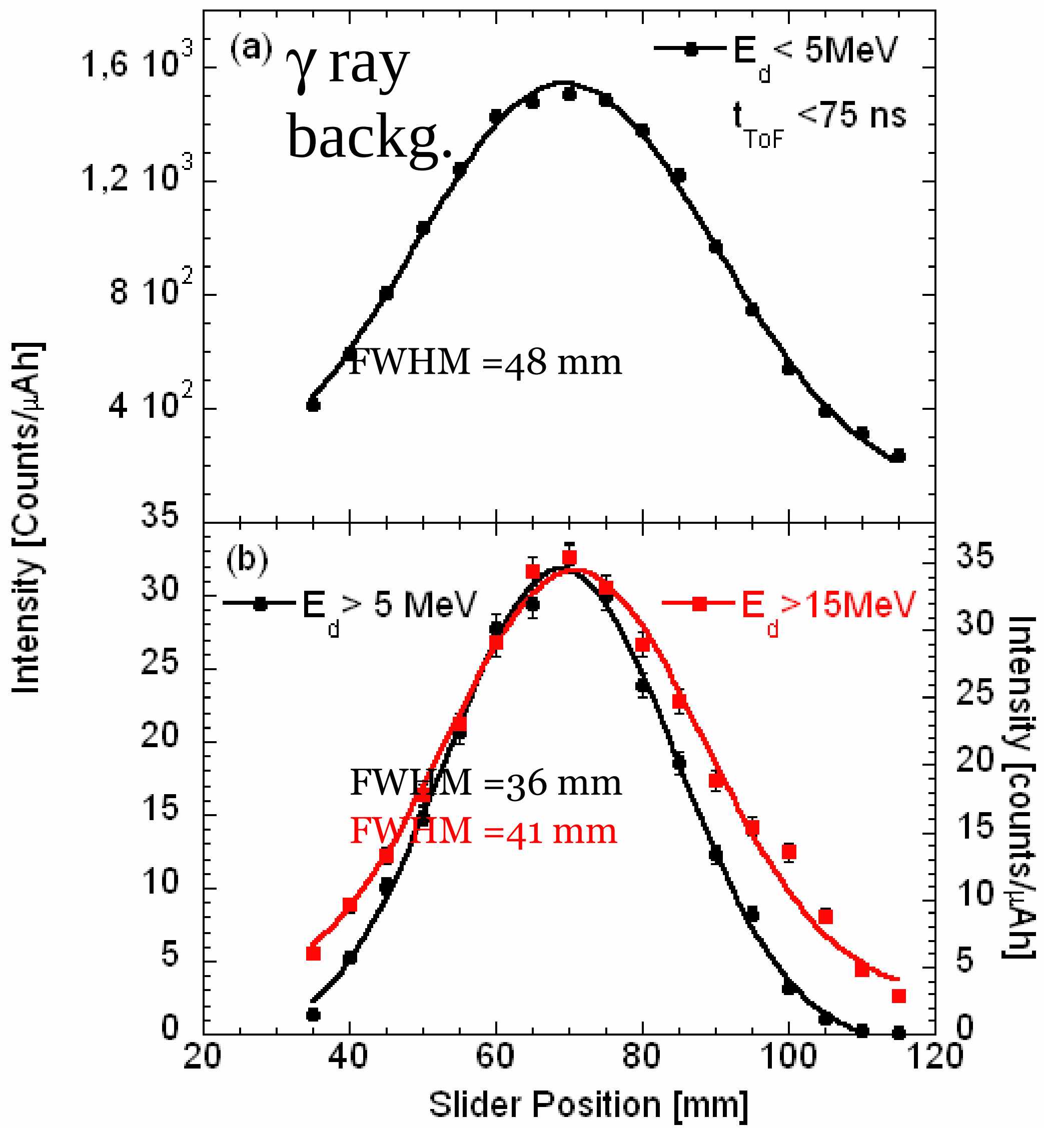
Time of flight spectrum for neutrons which deposit > 10 MeV and >20 MeV

Again a clear correlation between t_{ToF} and E_d is observed: the maximum t_{ToF} is shorter for the higher energy.

A neutron that deposits 10 MeV in the SDD should have E_n >15.7 MeV; that is t_{ToF} < 230±35 ns. A neutron that deposits 20 MeV should have E_n >25.7 MeV, i.e. t_{ToF} <182±35 ns.

→ For a quantitative analysis knowledge of the SDD response to monoenergetic neutrons is needed.

Beam profile measurement



Horizontal beam profile obtained by selecting events with:

- (a) E_d <5 MeV and t_{ToF} <75 ns,
- (b) E_d >5 MeV, 200 < t_{ToF} <250ns (black), and E_d >15 MeV (red).

The differences in profile width are well outside the uncertainties in the measurement.

nGEM Detector

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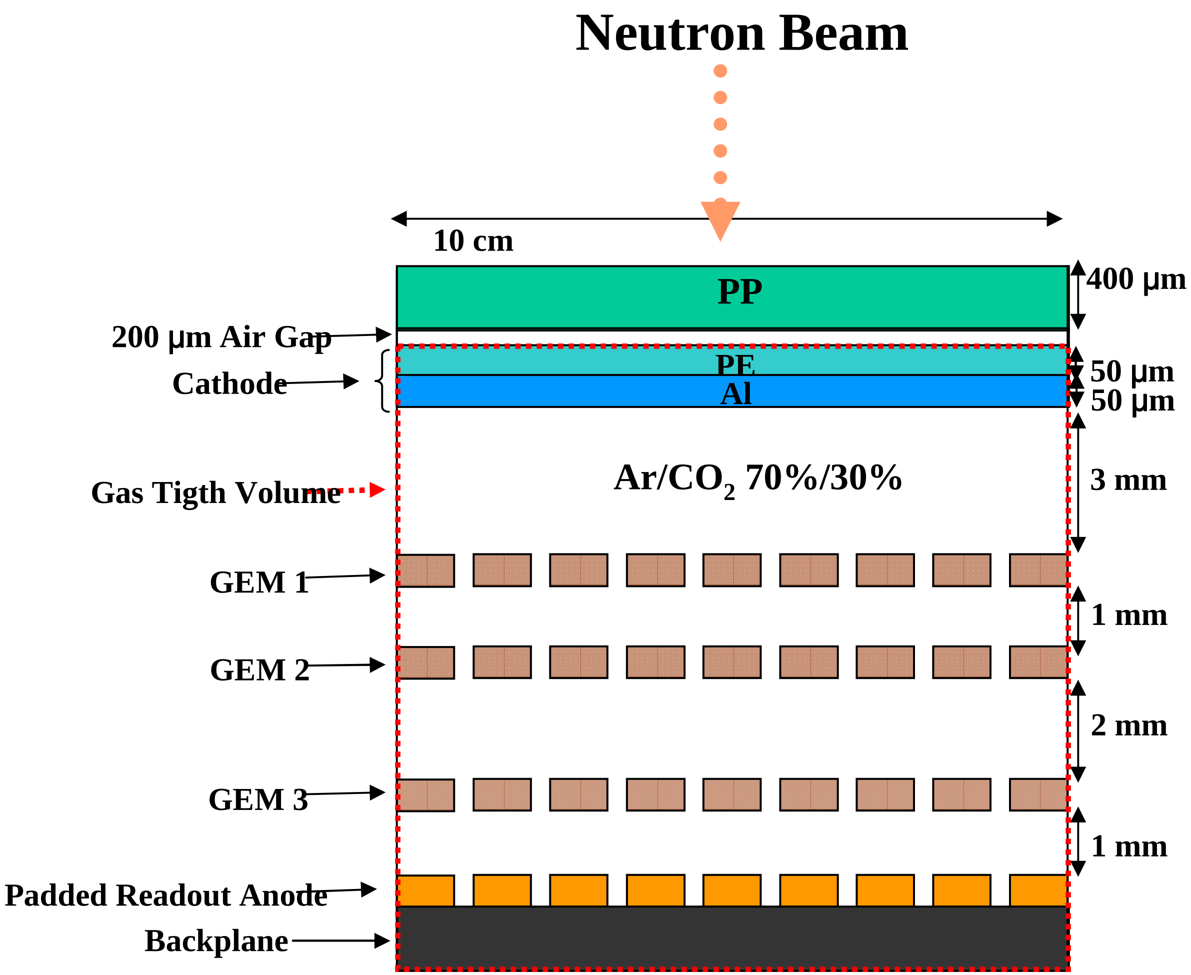

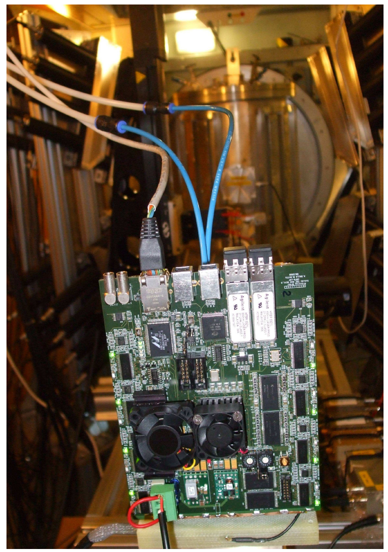

nGEM Detector Components

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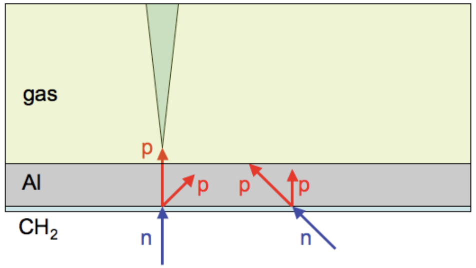
Optimized for 2.5 MeV neutrons detection

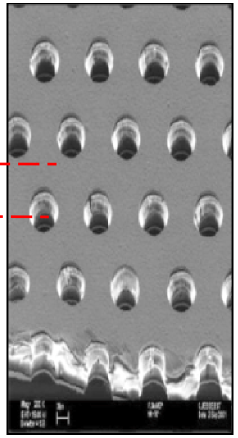
Converter Cathode

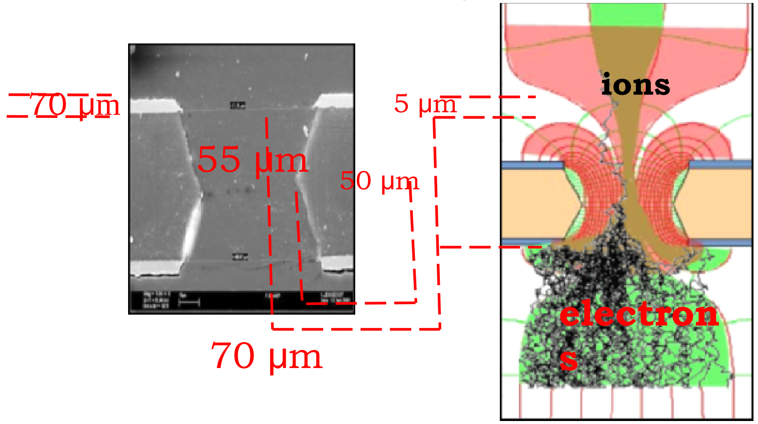
Composed by two layers of CH_2 50 um thick and of Aluminium 50 um thick

Recoil protons produced by neutrons release energy in the gas



GEM Foils

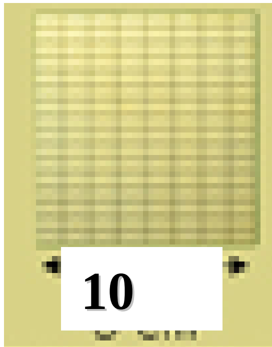




Padded Readout Anode

128 Pads

Pad Area 12 x 6 mm^2



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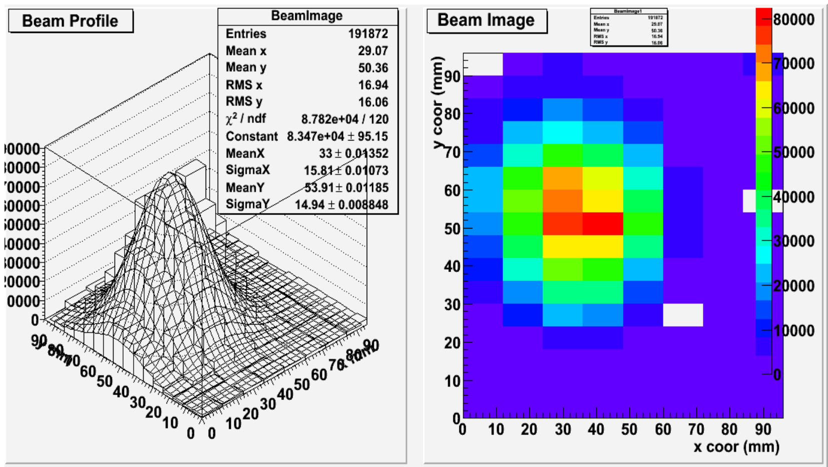
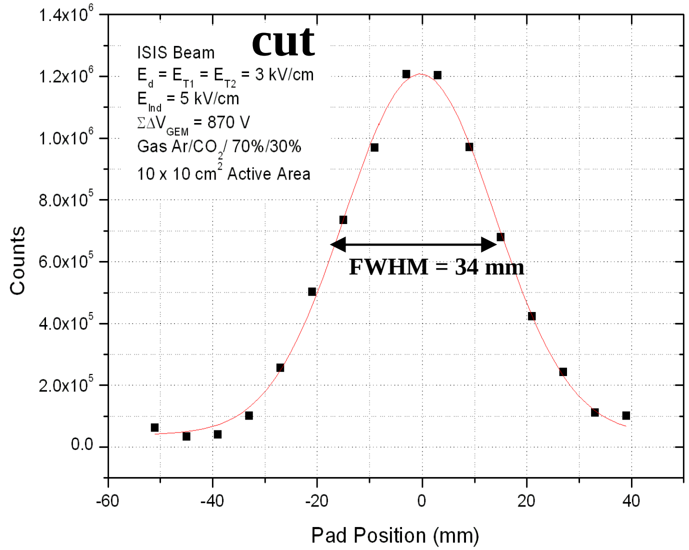
Vesuvio Beam Profile Measurement

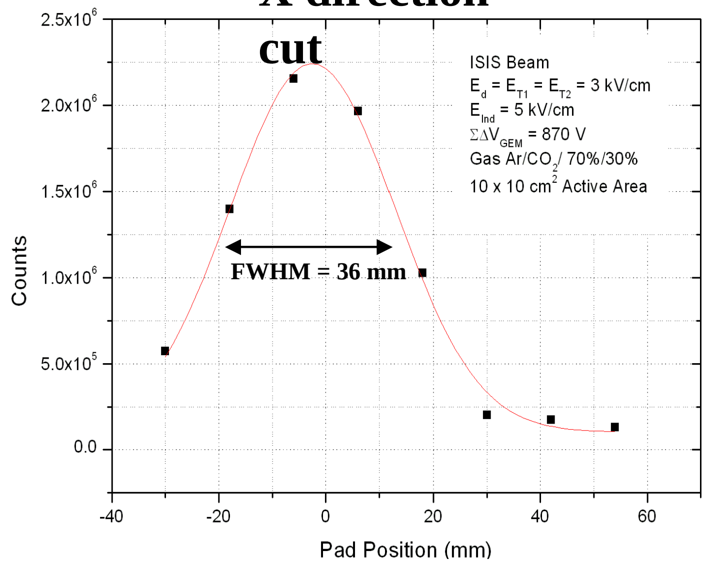
Fast Neutron Intensity Map



Y direction cut



X direction cut



Opening of Vesuvio shutter

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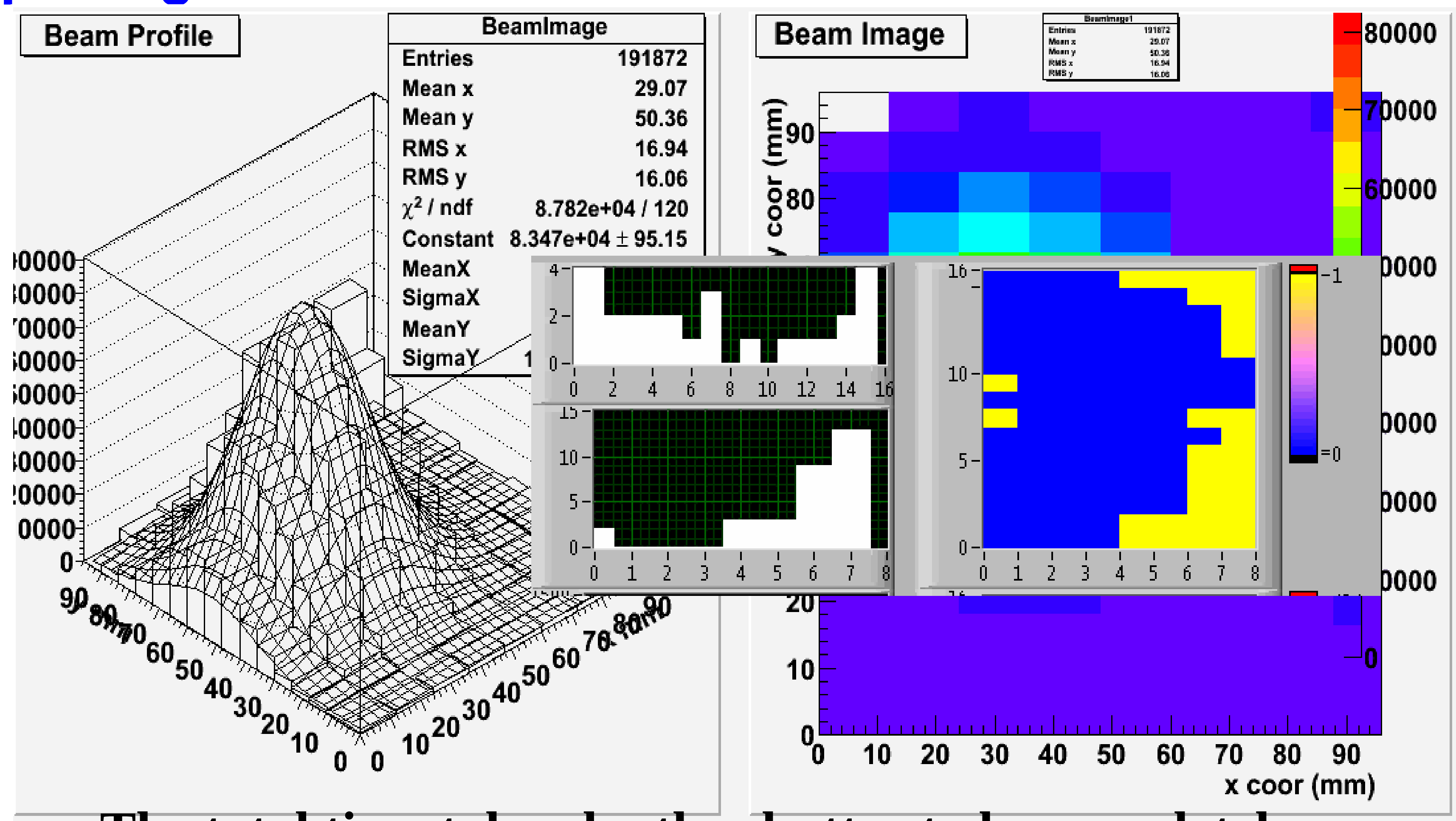

The total time taken by the shutter to be completely open is about 11 seconds

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