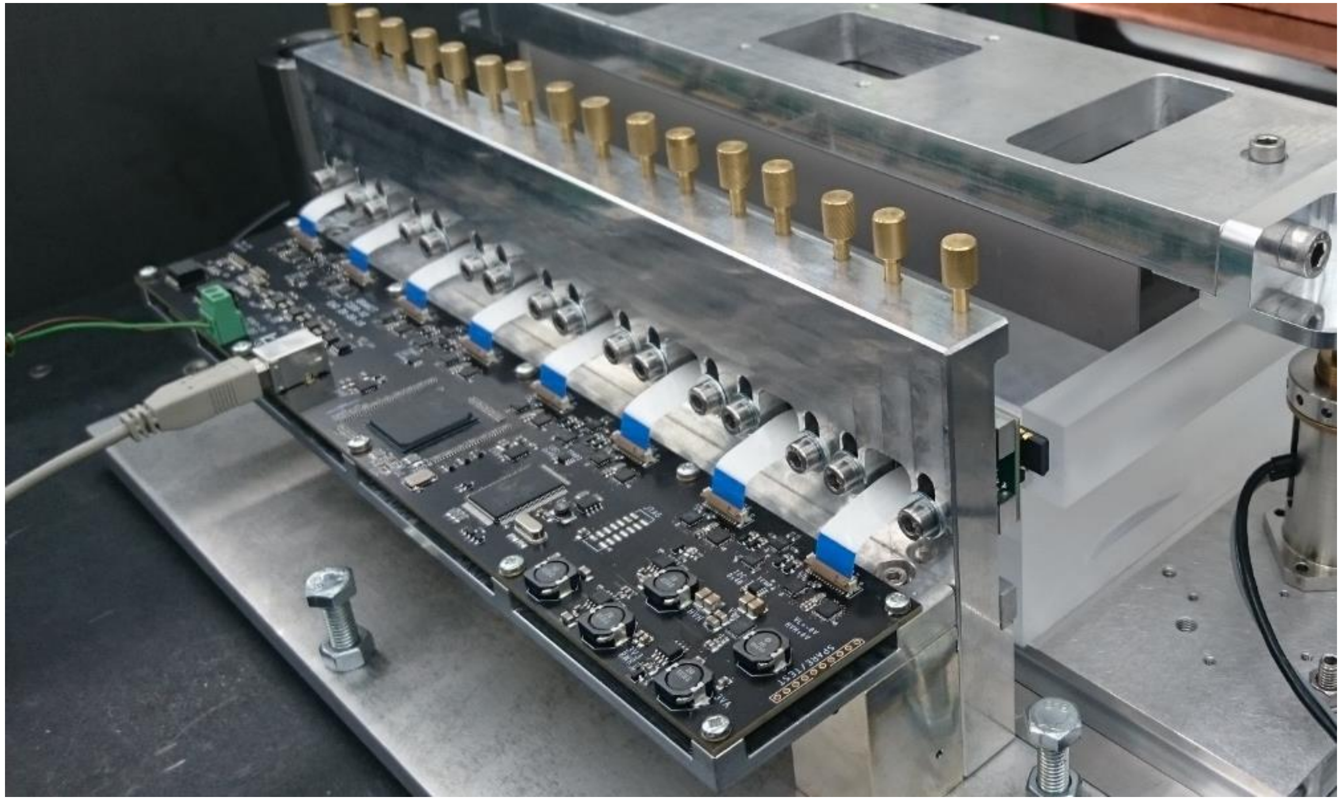
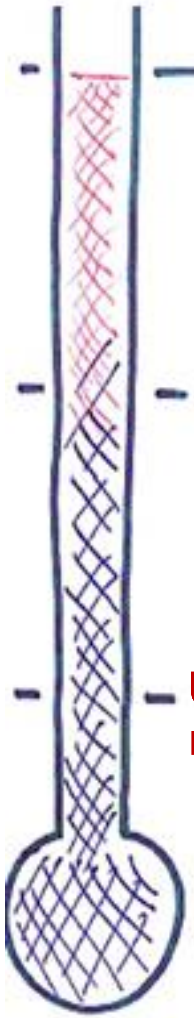
Spatial resolution of CCD based UCN detectors



Benoit Clément – VCI - 02/2022

Ultra-cold neutrons (UCN)



10 MeV — Fission fast neutrons

0.025 eV — Thermal neutrons

100 neV — Ultra−cold neutrons

Optical neutrons

When the neutron wavelength is greater than the interatomic distance
⇒ Coherent scattering on surfaces

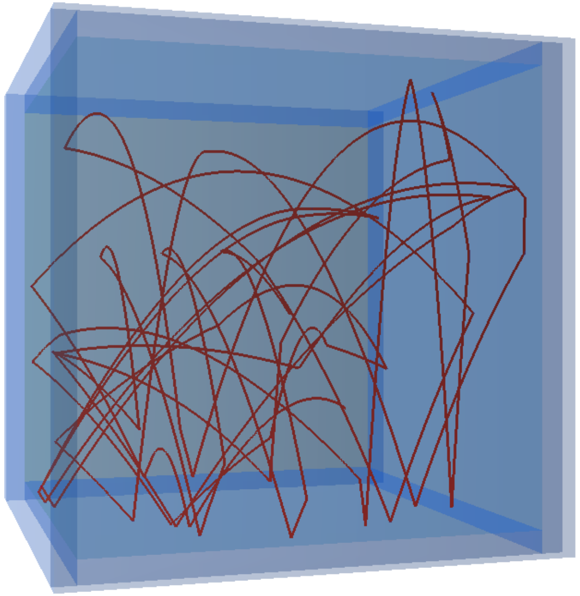
Characterised by an effective Fermi potential :

$$V = \frac{2\pi\hbar^2}{m_n} < b^{coh} >$$

For neutron energy < Fermi potential : neutrons are reflected on a surface at every incidence angle.
These are Ultra-cold neutrons :

$E < 250$ neV $v < 7$m/s $\lambda > 0.2$nm

4m/s neutron in a 50cm cubic box



UCNs can be stored in boxes,
guided by material tube,…

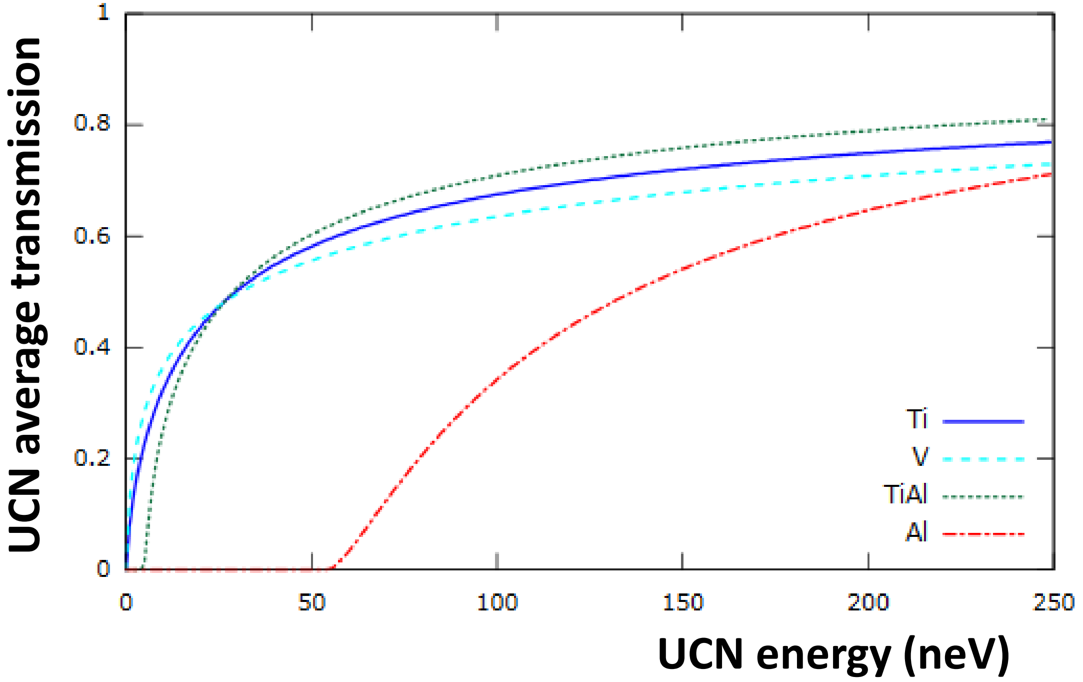
UCNS are sensitive to gravity :

$m_n g$ x (1m) = 100 neV

… but UCNs bounce of (most) detectors

UCNs detection

Neutron detection required a conversion material to produce charges particles (^{3}He, ^{10}B, ^{6}Li, ^{235}U, ^{238}Pu) or gamma rays (Gd,…)
For UCN, the Fermi potential must be taken into account



Gaseous detector (^{3}He), limiting factors :
- **Fermi potential of entrance window :**
- **Absobtion/scattering losses within the window : thin foils**

commonly used : Aluminum, titanium

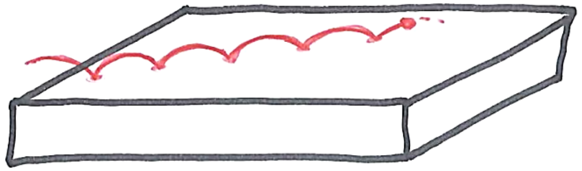
Solid detector
- **Fermi potential of the conversion layer**
- **Converted particle must escape the layer (Boron on silicon) or the conversion layer must be an active medium (LiF scintillators)**

^{6}Li : V_f = 28 neV
^{10}B : V_f = -3 neV (20% of nat. boron)

$n + {}^{10}B \rightarrow {}^7Li + \alpha$, BR = 6.3%
E_{Li}= 1014 keV E_α = 1775 keV

$n + {}^{10}B \rightarrow {}^7Li^* + \alpha \rightarrow {}^7Li + \alpha + \gamma$, BR = 93.7%
E_{Li}= 841 keV E_α = 1471 keV

Quantum freefall and position sensitive detectors



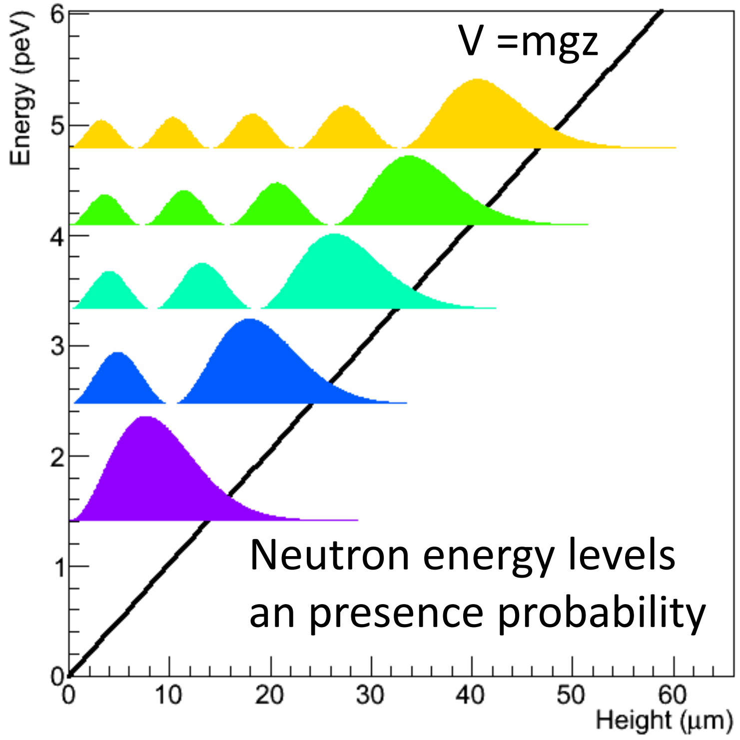
We study the quantum free fall of a neutron : Bound state in a vertical potential mgz

Schrödinger equation : $\left(\frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial z^2} + m_g g z\right)\psi = E\psi \Rightarrow \left(\frac{\partial^2}{\partial Z^2} + Z\right)\psi = 0$

Airy equation

With : $z_0 = \left(\frac{\hbar^2}{2m_i m_g g}\right)^{\frac{1}{3}} \approx 5.87\mu m$ $E_0 = m_g g\, z_0 \approx 0.602\ \mathrm{peV}$ $\epsilon = \frac{E}{E_0}$ $Z = \frac{z}{z_0} - \epsilon$

Boundary conditions $\psi(0) = \psi(+\infty) = 0$ quantify the energies E_k:



Neutron energy levels
an presence probability

Two kind of observables

Quantified energies: transition between levels

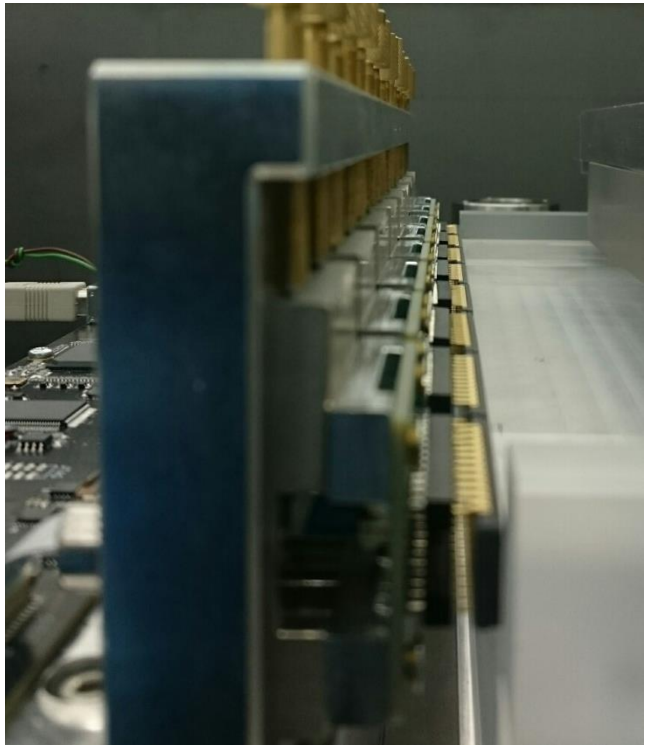
Wavefunction : shape, nodes positions.

Need position sensitive detector with micrometric resolution

The UCNBox detector

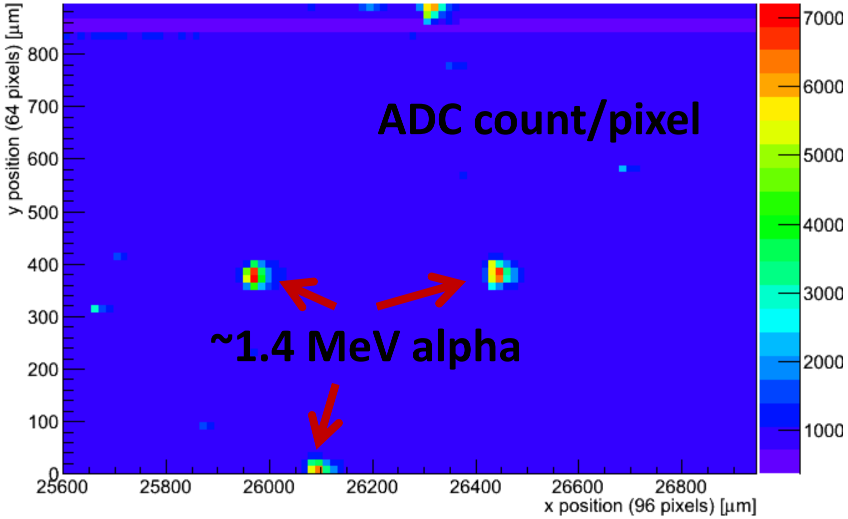
To get a spatial information we use CCD sensors as charge particle detectors

- window less back-thinned CCD (Hamamatsu)
- 2048x64 pixels, 14x14 µm



UCN Boron piXels detector :

- line of 8 sensors (30 cm) to adapt to the GRANIT installation at ILL to observe neutron wavefunctions
- mechanical support for alignment
- dedicated electronics *O. Bourrion et al. NIM. A880 (2018)*

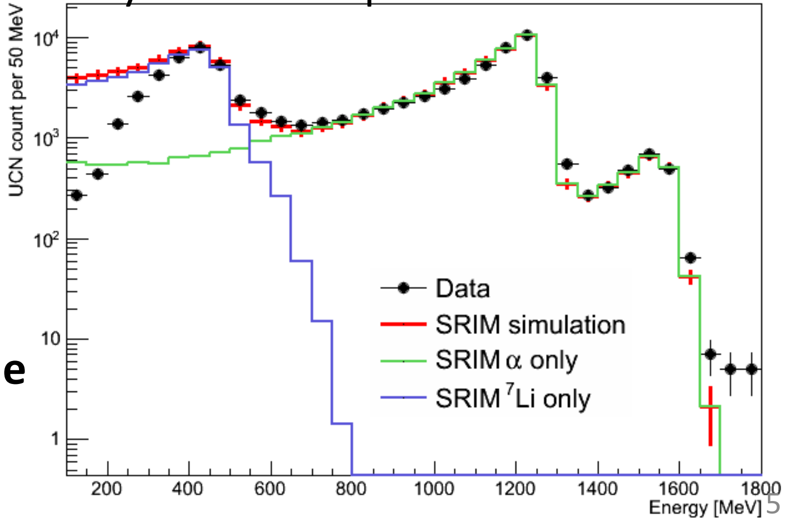


1 charge particle (1.4 MeV α) deposits energy in several pixels

Reconstruction strategy :

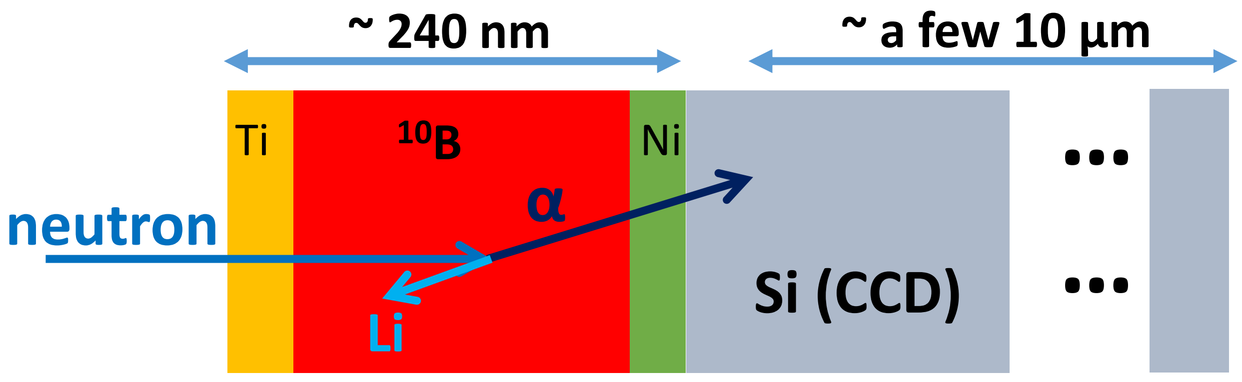
- build 11x11 pixels clusters around «seed» pixels
- the cluster barycenter gives the particle position
- the cluster mean ADC count gives the energy

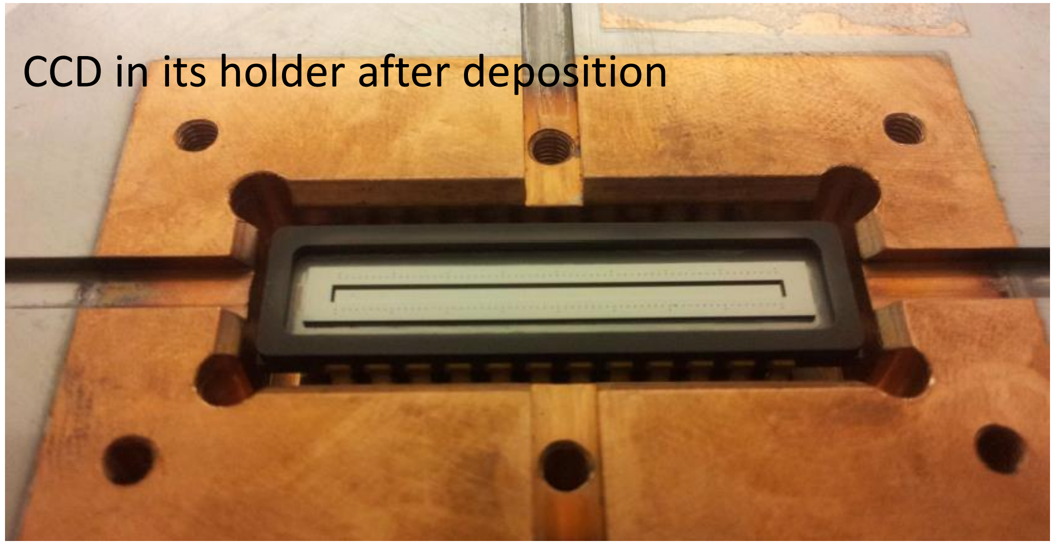
Measured energy of α/Li produced by neutron capture on ^{10}B

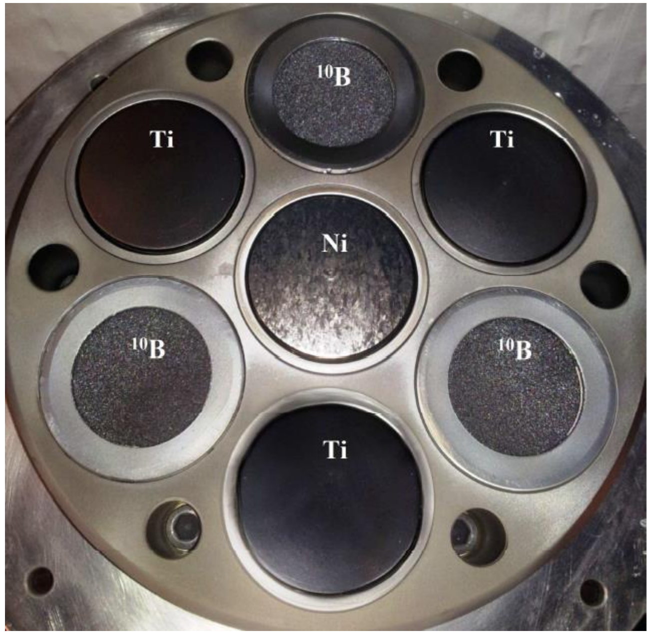


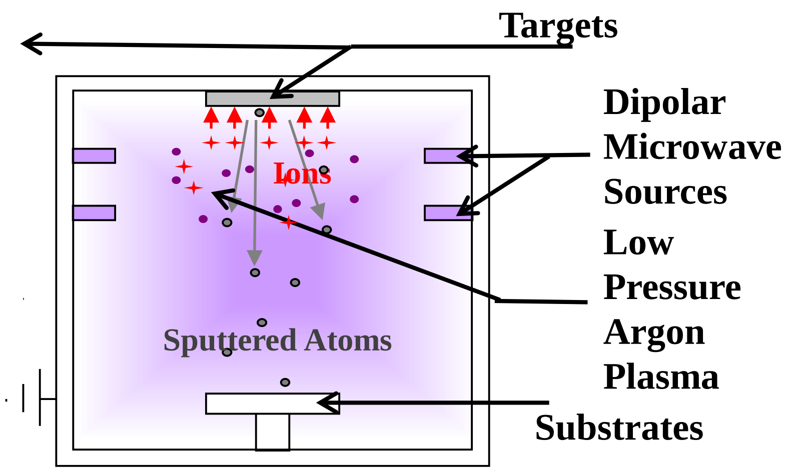
Realisation of the multilayer

Multilayer Ti-B-Ni deposed using microwave plasma-assisted cosputtering method

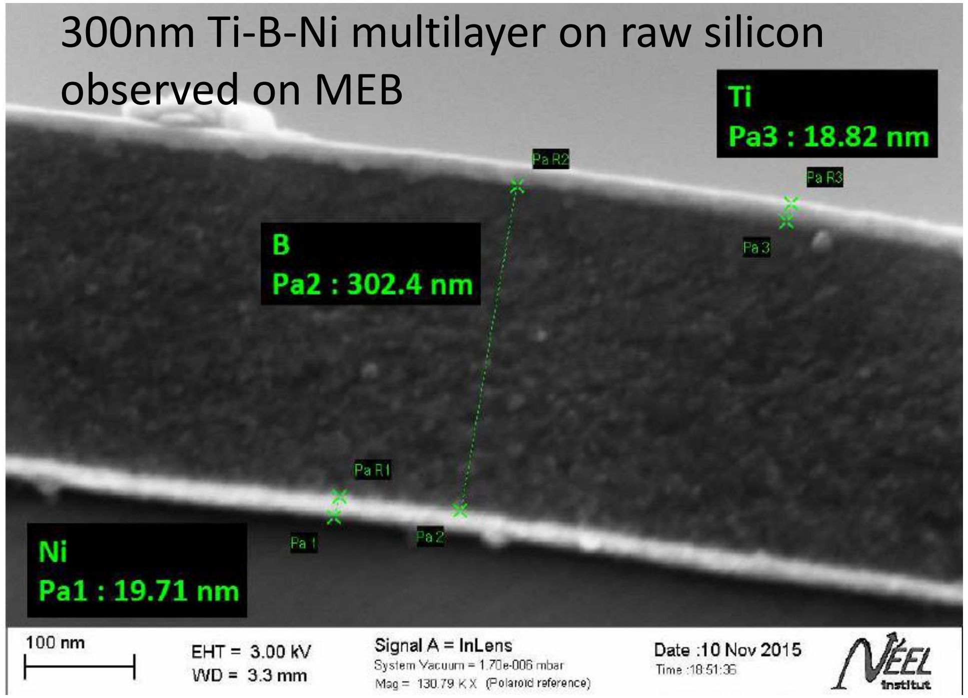



CCD in its holder after deposition

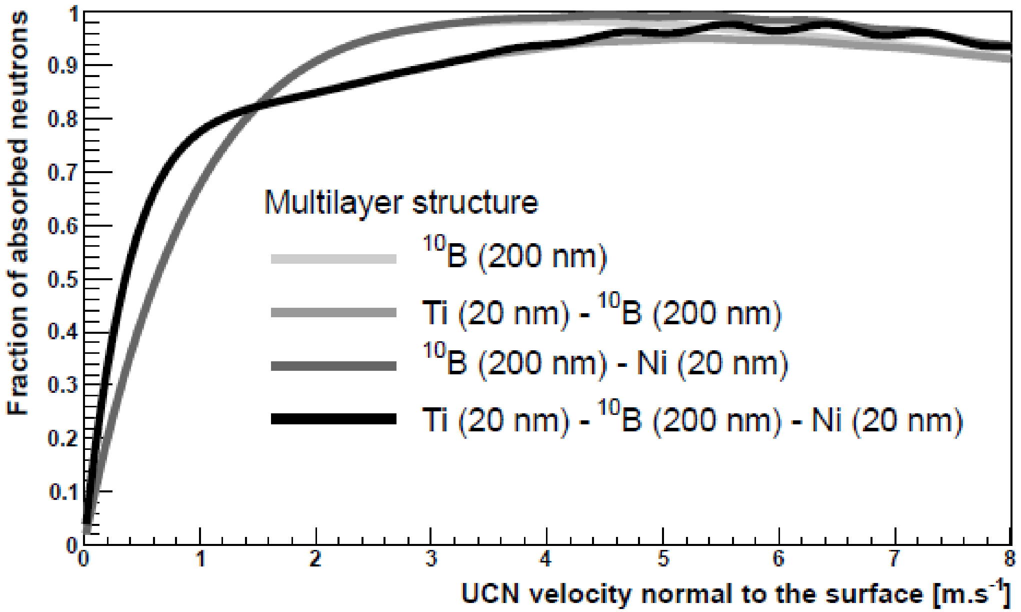


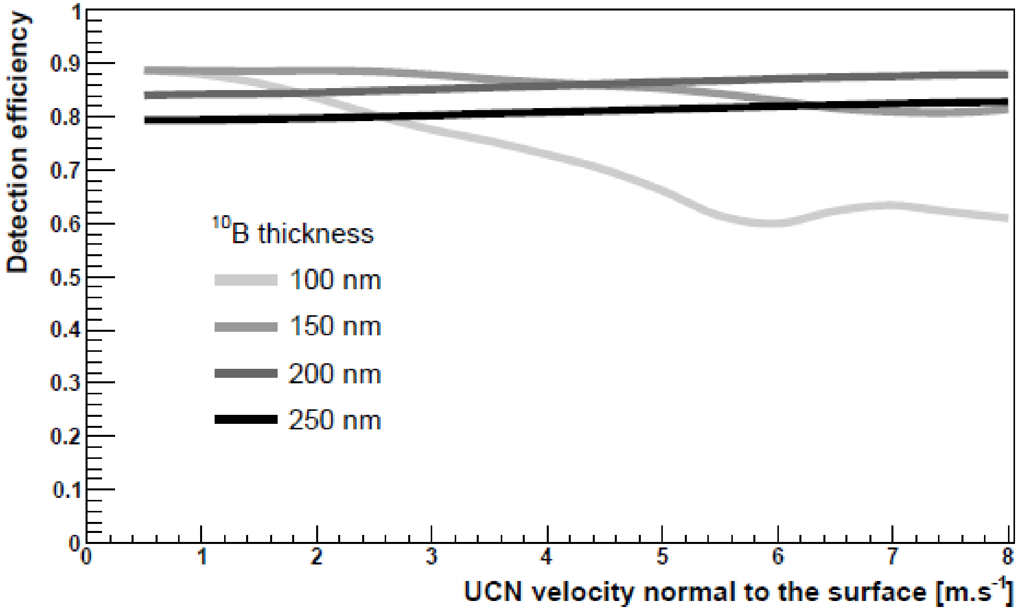


300nm Ti-B-Ni multilayer on raw silicon observed on MEB



Ti-B-Ni conversion multilayer and efficiency





B.C. et al, *JINST* 14 (2019) 09, P09003

The conversion layer devised is :

20 nm entrance Ti layer

- **→ reduce reflection at low velocities**
- **→ protects boron from oxidation**

200 nm conversion ^{10}B layer

- **→ optimum to convert UCNs and let charged particles out of the layer**

20 nm back Ni layer

- **→ reflect hich velocities UCN**
- **→ improve boron adhesion on silicon substrate**

Efficiency (almost) is independent on velocity. estimated : 84% to 88%, measured : 82±9 %

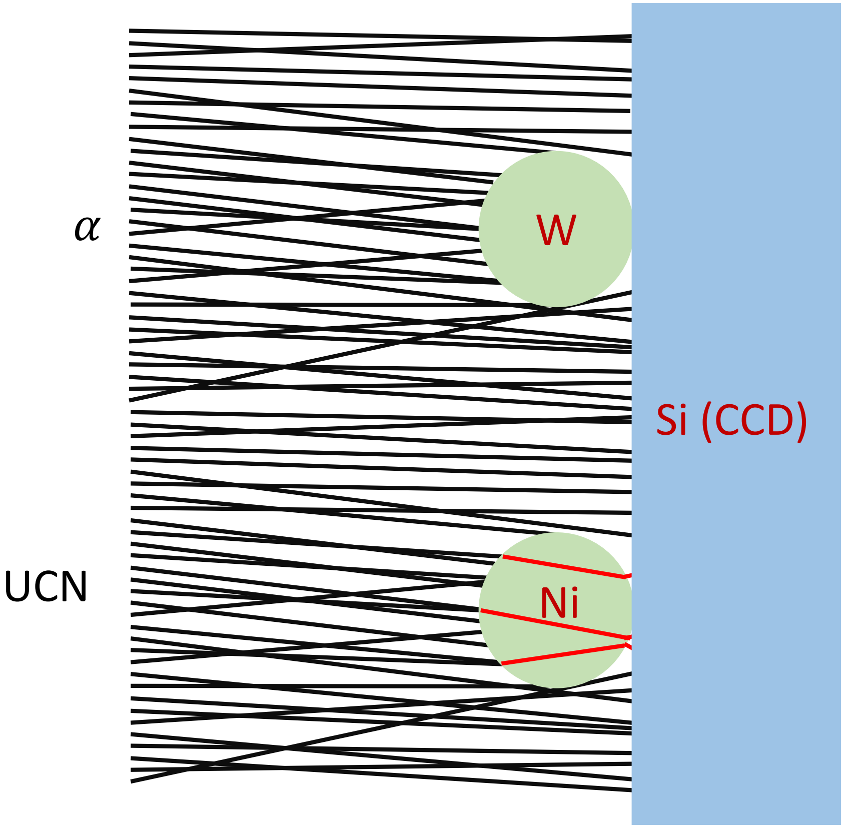
Measuring the spacial resolution

Place a piece of wire on the sufrace of the CCD
« Light » with neutrons or α particles and detect the wire shadow

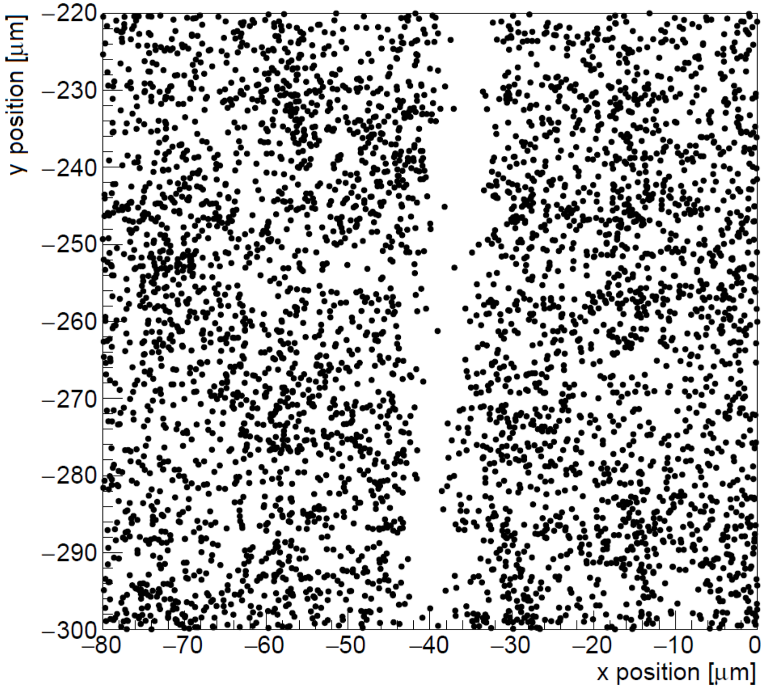
Two datasets :

- **1.5MeV α particles over 6µm tungsten wire (no boron layer)**
- **UCN over 10µm Ni wires -> at ILL PF2 Test line**

Approximtively 2.4mm of usable Ni wire and 3.5mm of W.
A few days of data, 0.5 to 0.7 particle per µm²



Reconstructed α positions around a W wire



Problems

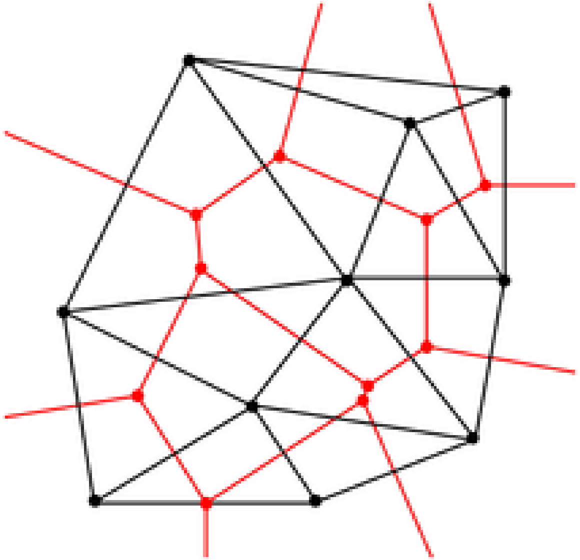
- **Reconstruction the position and direction of the wire**
- **Projection along this direction and combining several wires**
- **Exctraction of the resolution : need MC simulation**
- **Quantifying the systematics**

Estimation of density of points

Delaunay triangulation :

Given a set of points in 2D, find the triangle meshing that maximise the smallest angle of each triangle (tringle less flats as possible)

Standard tool for meshing in finite elements calculation : many optimized algorithms and freely vailable codes !



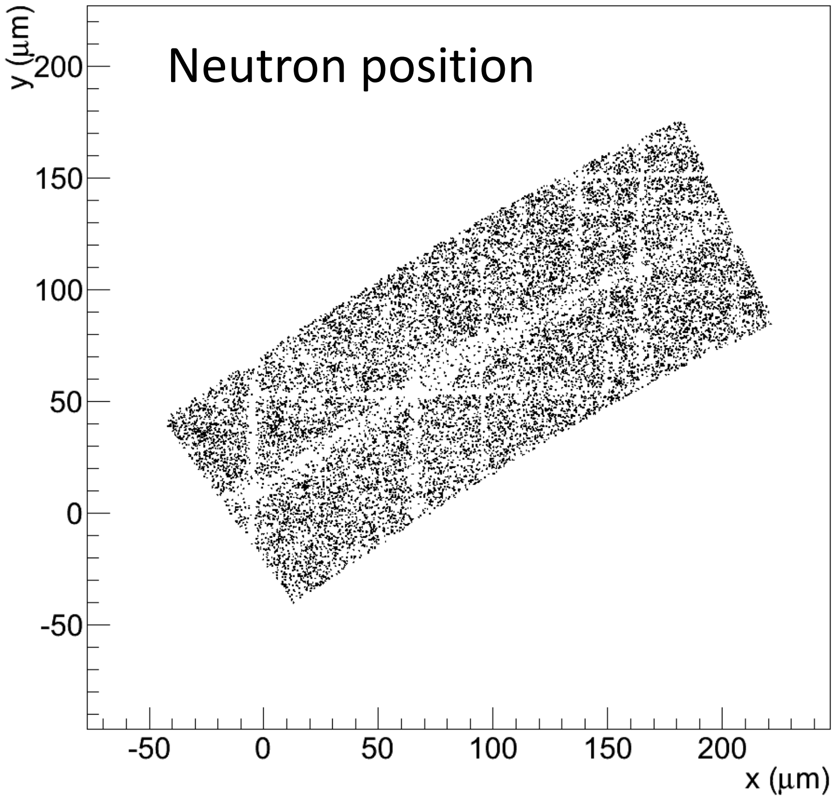
Voronoi diagram :

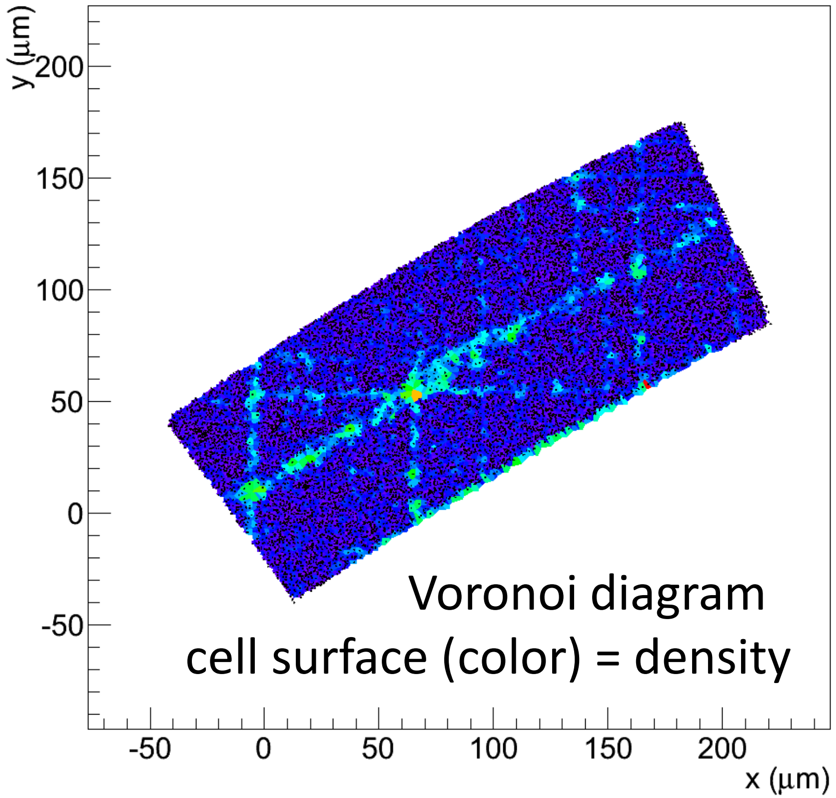
compute the median of each segment in the Delaunay trangulation and compute their first instersections.

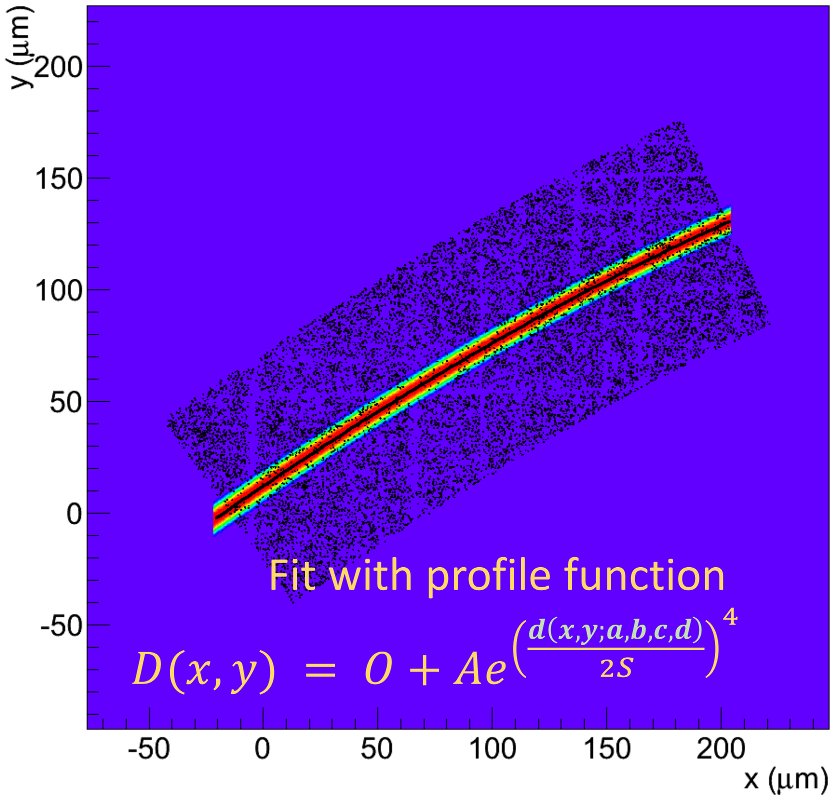
each original point is contained within one Voronoi cell, the surface can be used as a (inverse) density estimator : used in cellular biology, geography,…

Wire direction

Cut each wire in ~200µm segments, and manually select a band around the wire


Neutron position


Voronoi diagram
cell surface (color) = density


Fit with profile function

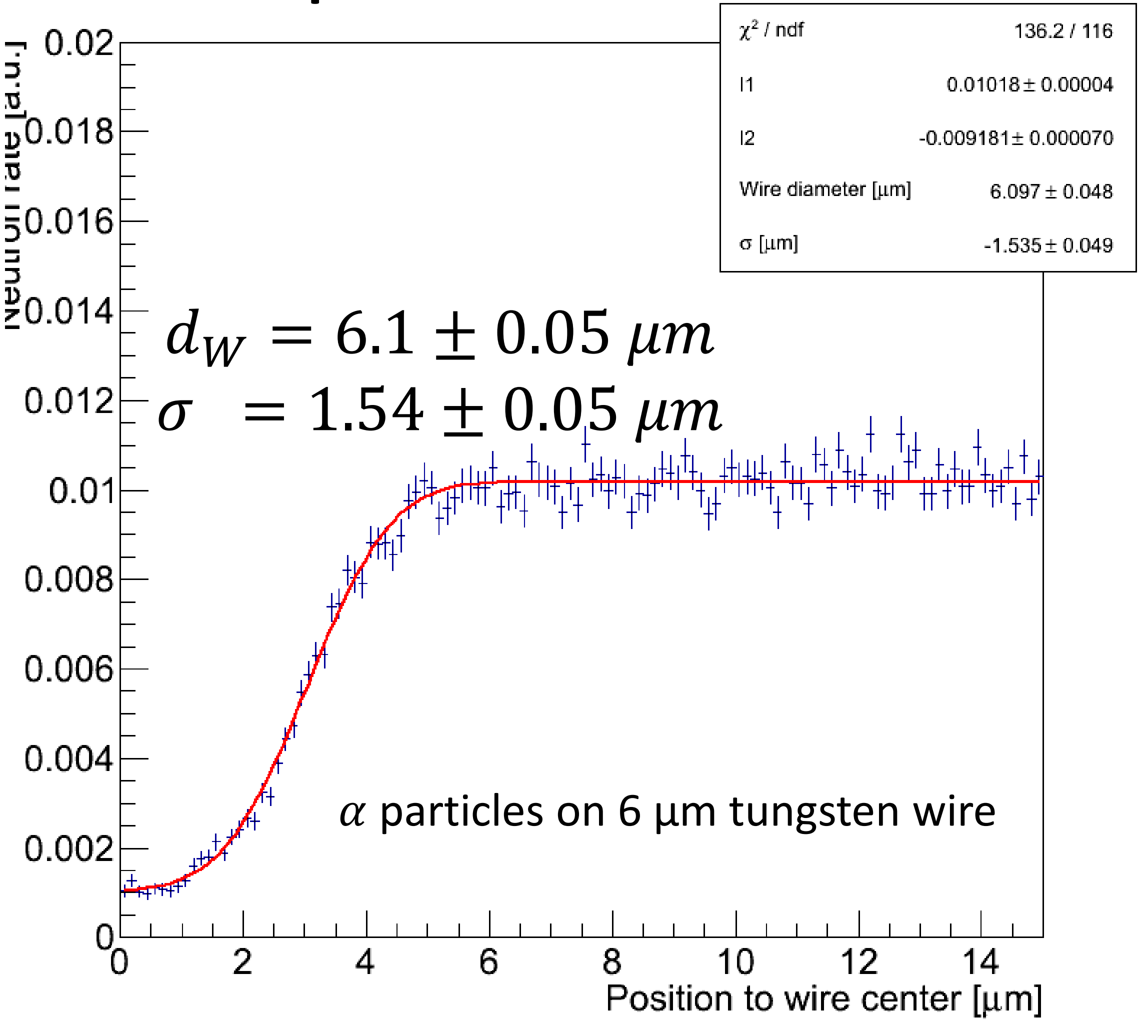
$$D(x,y) = O + Ae^{\left(\frac{d(x,y;a,b,c,d)}{2S}\right)^4}$$

$d(x, y; a, b, c, d)$: distance of point (x, y) to the polynomial curve $y = ax^3 + b^{x^2} + cx + d$

Histograms of d gives the projected wire profile

Projected wires

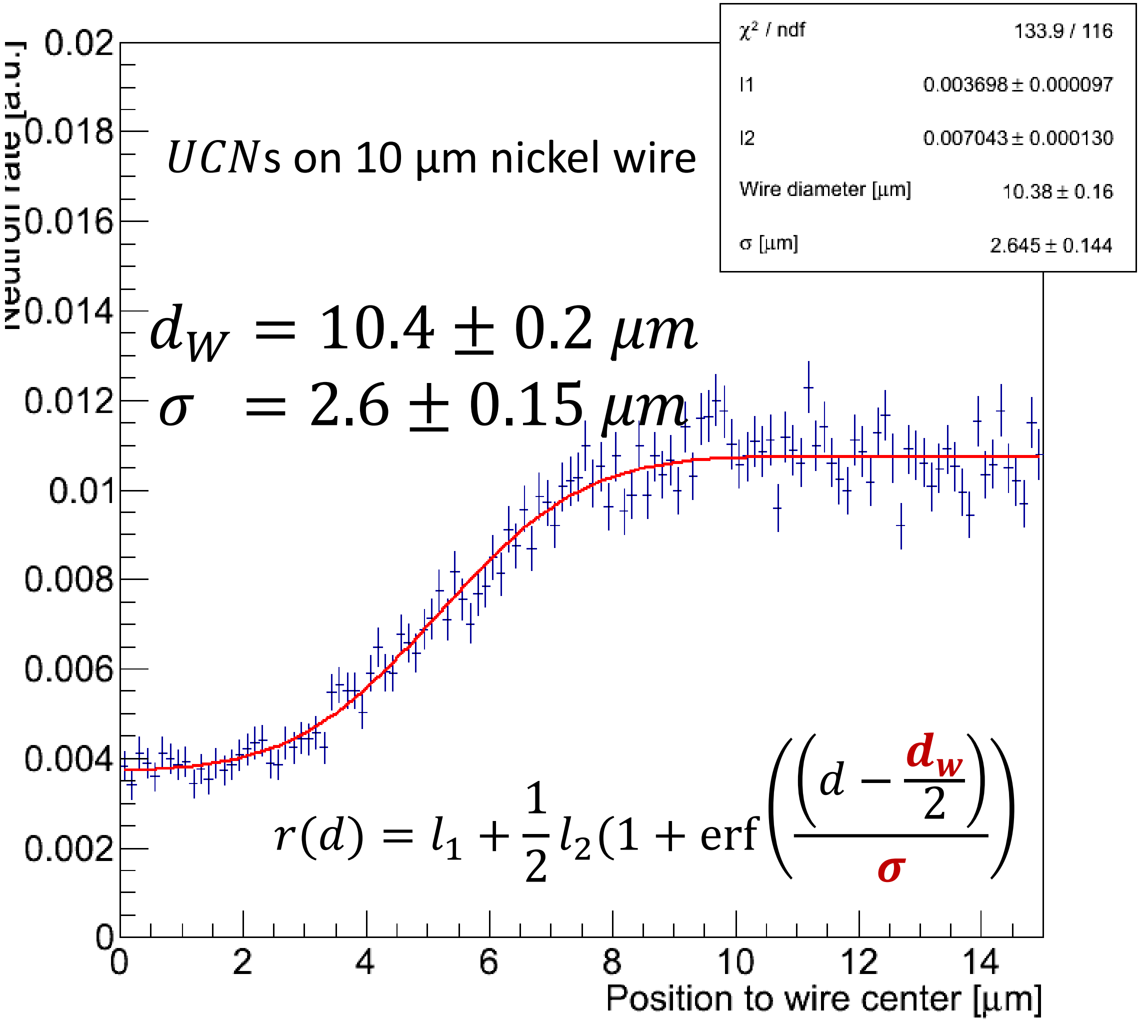
The wire profile is fitted with an Erf function



$d_W = 6.1 \pm 0.05\ \mu m$

$\sigma\ = 1.54 \pm 0.05\ \mu m$

α particles on 6 μm tungsten wire



UCNs on 10 μm nickel wire

$d_W = 10.4 \pm 0.2\ \mu m$

$\sigma\ = 2.6 \pm 0.15\ \mu m$

$$r(d) = l_1 + \frac{1}{2} l_2 (1 + \mathrm{erf}\left(\frac{\left(d - \frac{\boldsymbol{d_w}}{2}\right)}{\boldsymbol{\sigma}}\right)$$

The fitted σ is not the resolution yet has it includes shadowing effects due to the wire shape and diffusion of fastets UCNS through the wire.

Conversion to resolution

Use Monte-Carlo simulation to compute the conversion curve from fitted resolution to actual resolution.

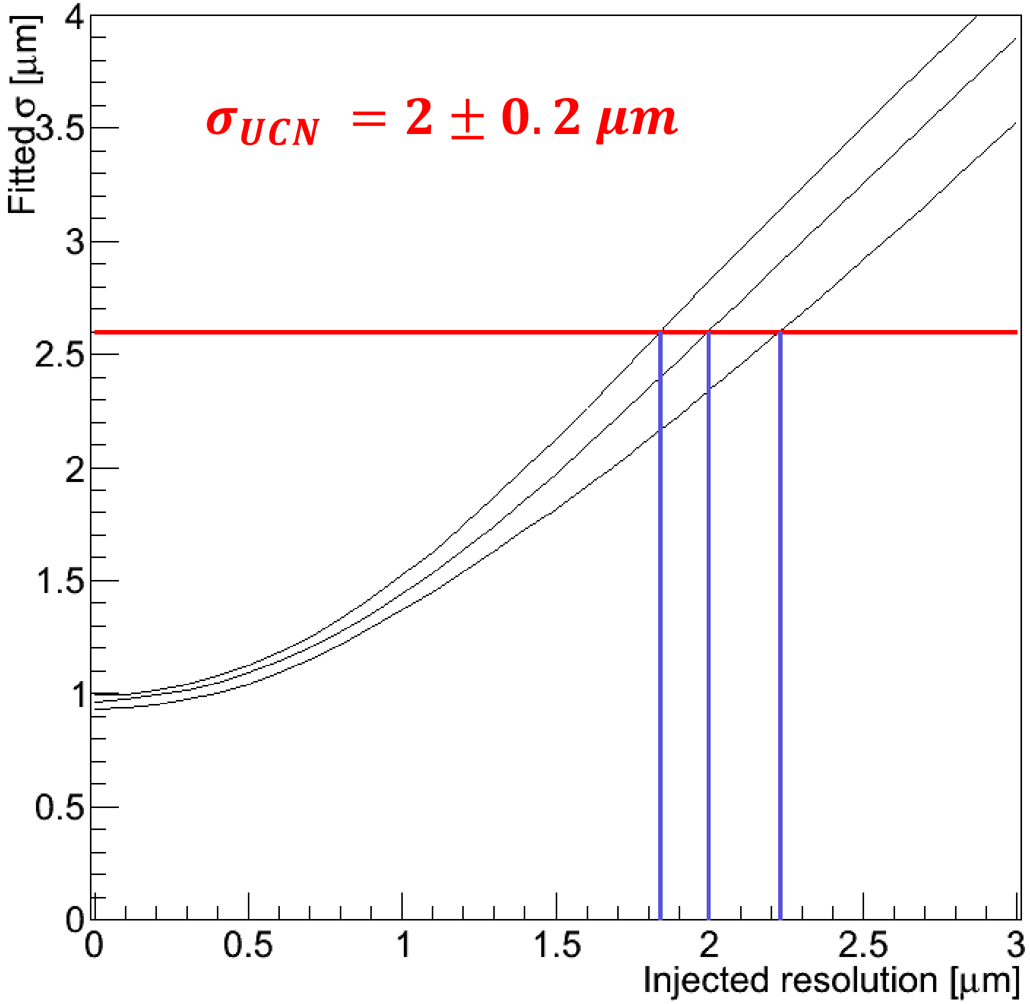
Some uncontrolled parameters

- **diffusivity of the wire surface**
- **velocity spectrum of UCNs**

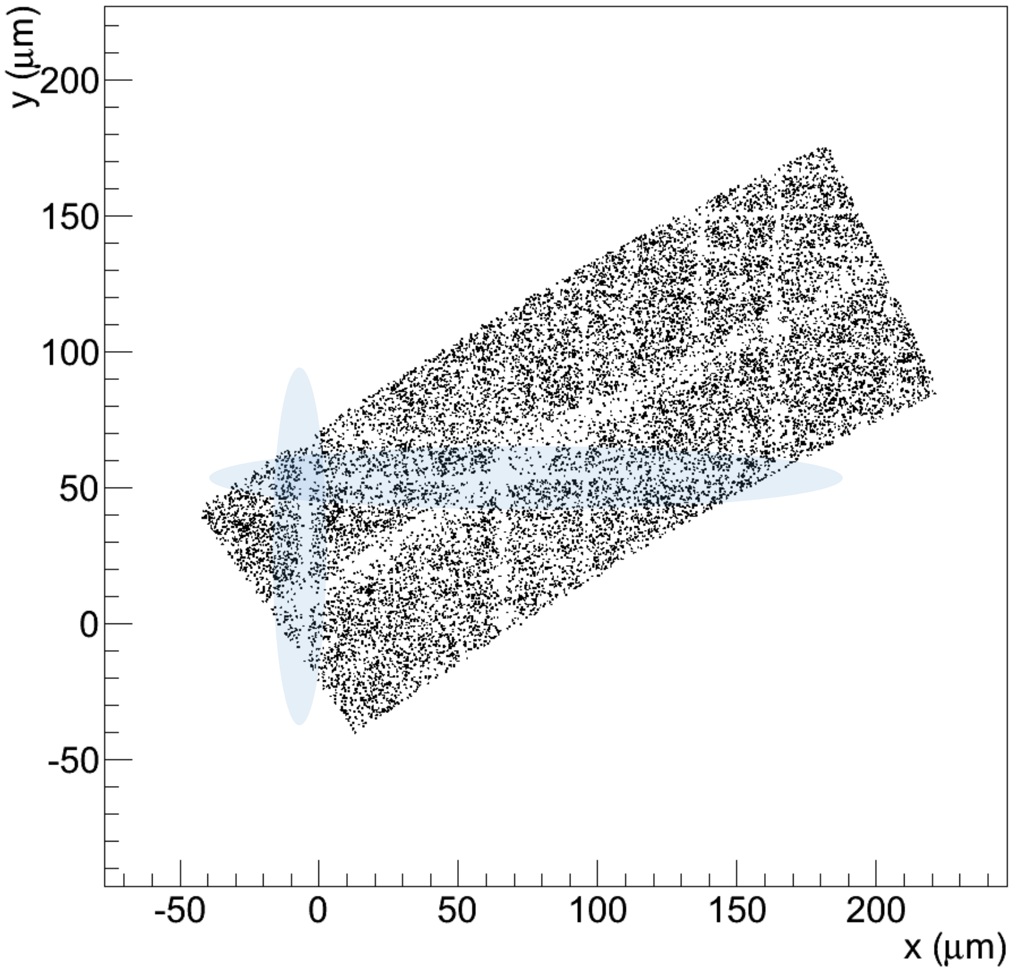
Similar exercise for alpha particles leads to

$$\boldsymbol{\sigma_\alpha = 1 \pm 0.1\ \mu m}$$

The systematic effect due to the reconstruction and fitting procedure is estimated by building fake wire images using the fitted parameters : $\boldsymbol{\sim 0.3 \mu m}$



Sensor aging and hot pixels



Looking at the data, one noticies depleted vertical and horizontal lines

→ 11x11 squares around « hot » pixels (pixels with sometimes large noise that tend to displace the reconstructed hit toward them)

→ didn't appear in older measurement : degradation of sensor over time (multilayers are >3 years old, sensors kept in contact with air in a clean room)

→ Impossible to correct, but can be simulated : this effect alone leads to :

$$\sigma_{fit} = 1.9 \pm 0.2\ \mu m \Rightarrow \sigma_{UCN} = 1.5\ \mu m$$

Quadratically substracting to the previous result, one could extrapolated an expected resolution for a freshly coated sensor to

$$\boldsymbol{\sigma_{UCN} = \sim 1.3\ \mu m}$$

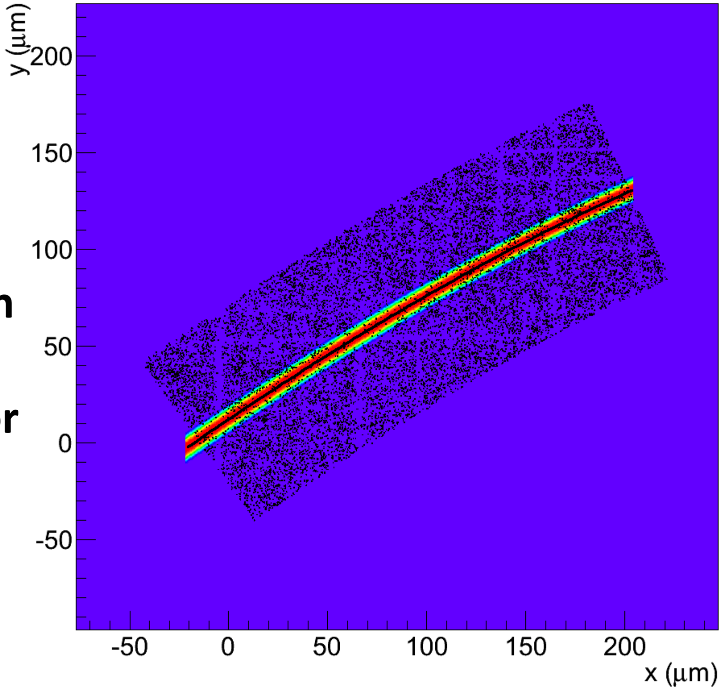
Summary and conclusion

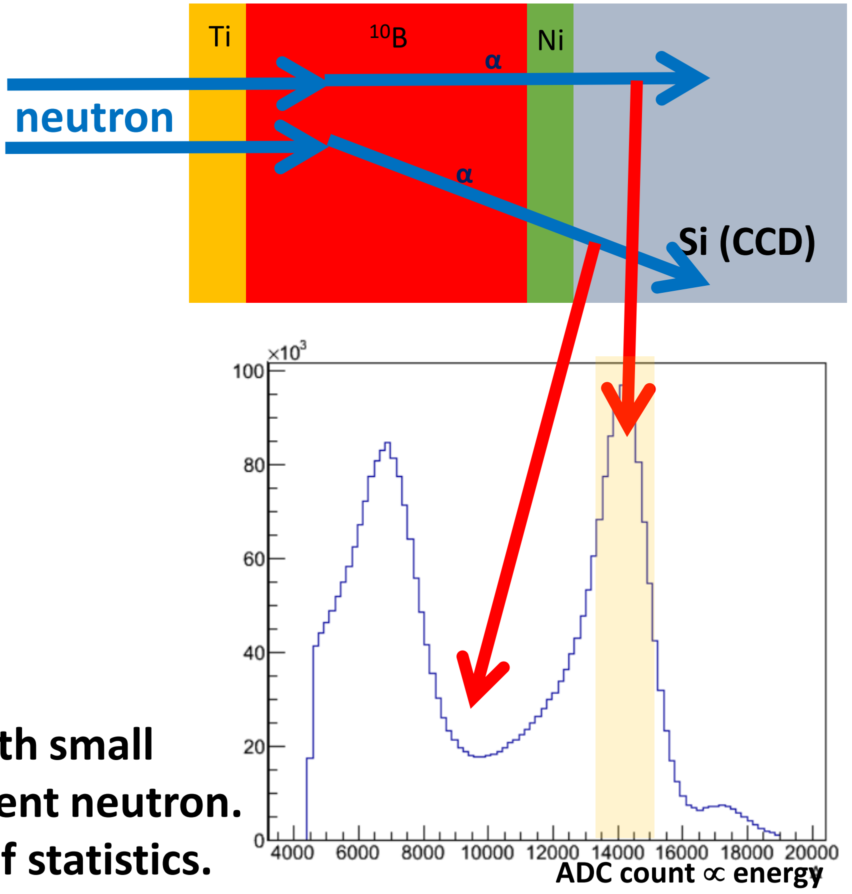
UCNBox is a UCN detectors using 8 CCD sensors coated with a Ti-^{10}B-Ni multilayer with an efficiency of 84% designed to measure wavefunctions of free falling neutrons bouncing on a mirror.

A complete procedure to determine experimentaly the spatial resolution has been developped using the shadow of a thin wire in contact with the conversion layer
The measured resolution on an «old» sensor is :

$$\boldsymbol{\sigma_{UCN} = 2 \pm 0,2(stat) \pm 0,3\ (syst)}\ \text{µm.}$$

and the resolution of a fresh sensor could lower to 1,3µm.





One possible improvement : **Use the energy of the α/Li to select particles with small energy loss, having a small angle w.r.t. the incident neutron. This should improve the resolution at the cost of statistics.**