Neutron spectrometry for medical and industrial accelerators

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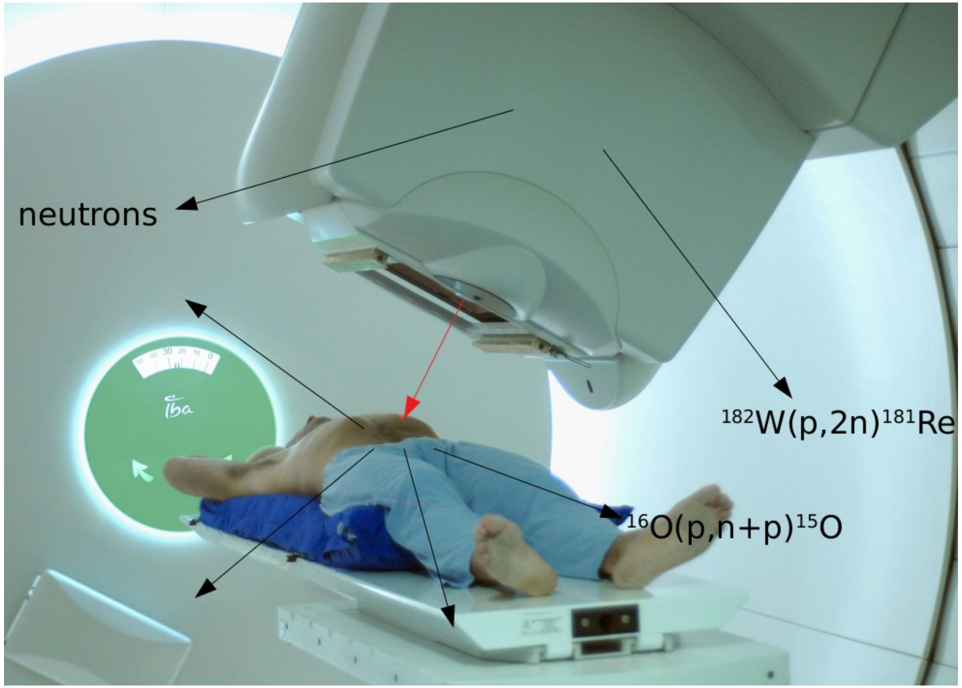
Summary

- Context
- Recoil Proton Telescope
  - Principle
  - Simulation & analysis :
    - Background elimination
    - Efficiency
    - Neutron energy resolution
  - Diode calibration
- Conclusion and prospects

Context

Neutrons are one of the most produced particles nearby particle accelerators :



IBA Proteus series

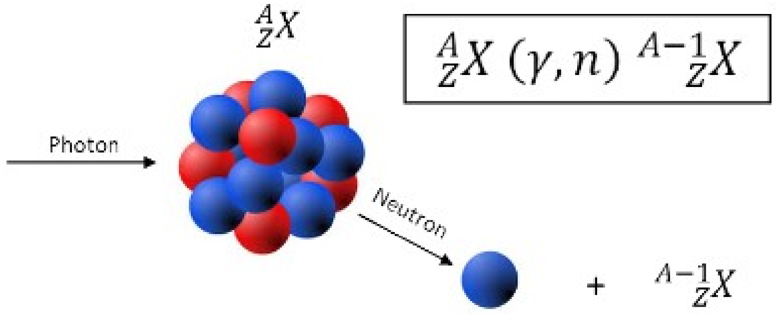
Hadrontherapy :

- Neutrons produced in the accelerator head and patient body itself
- Neutron dose is badly or not even calculated by TPS (out-of-field dose)
- Need to better estimate the secondary neutrons production (measurements + calculations)

Context

Industrial irradiation :

- Increasing use of linear accelerators :
  - Photo-nuclear activation >2 MeV
  - Risk of contact/ingestion of activated nucleids
- Controls by gamma spectrometry but some detection limits (counting time, etc.)



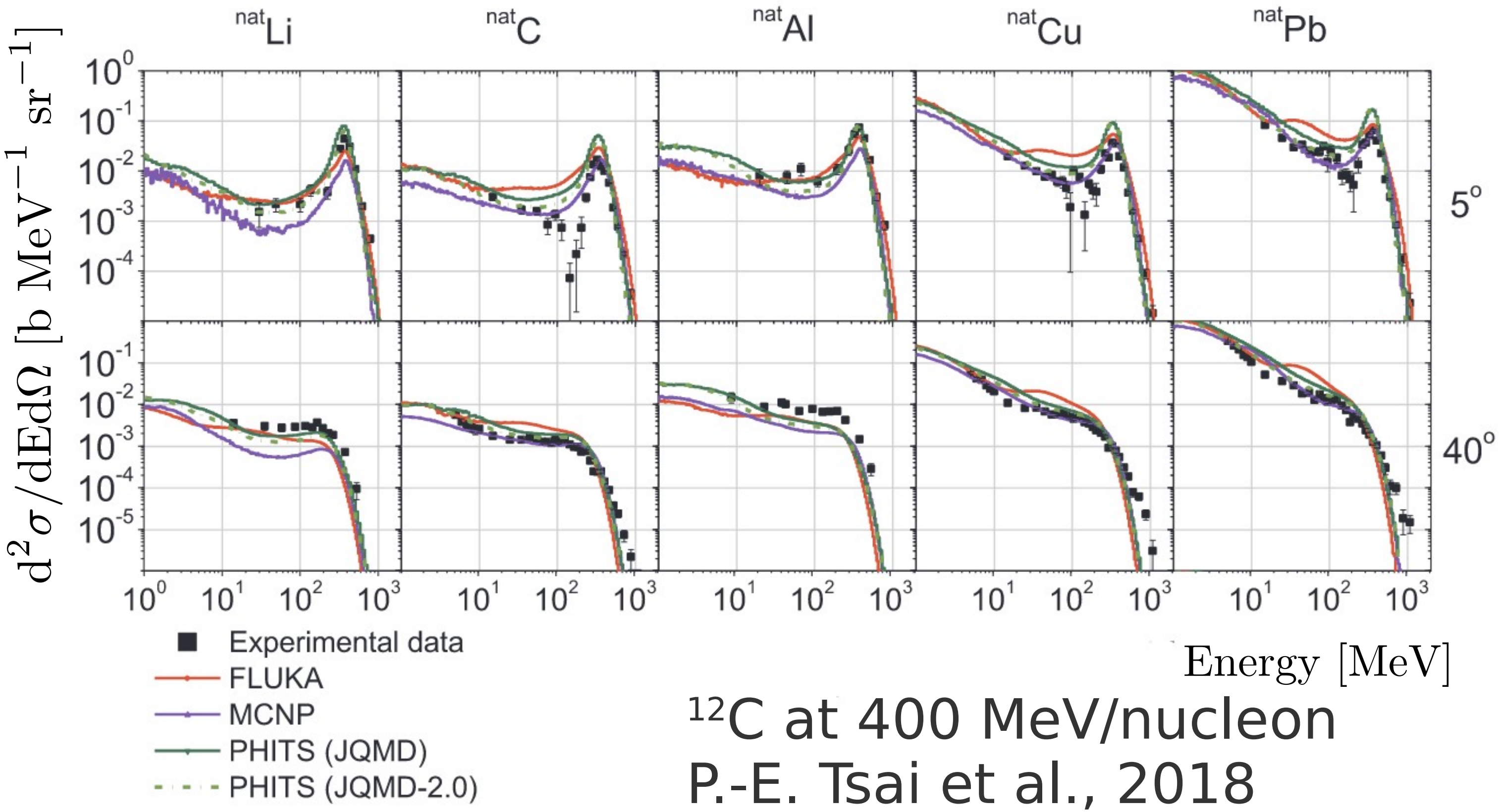
Direct and indirect activation : $\gamma \rightarrow n$ and $n \rightarrow \gamma$

$^{204}Pb\ (\gamma,n)\ ^{203}Pb$ $^{13}C\ (n,\gamma)\ ^{14}C$

→ Measurements completed by Monte Carlo simulations

Context

Discrepancies between Monte-Carlo predictions and actual data, depending of nuclei and energy



^{12}C at 400 MeV/nucleon
P.-E. Tsai et al., 2018

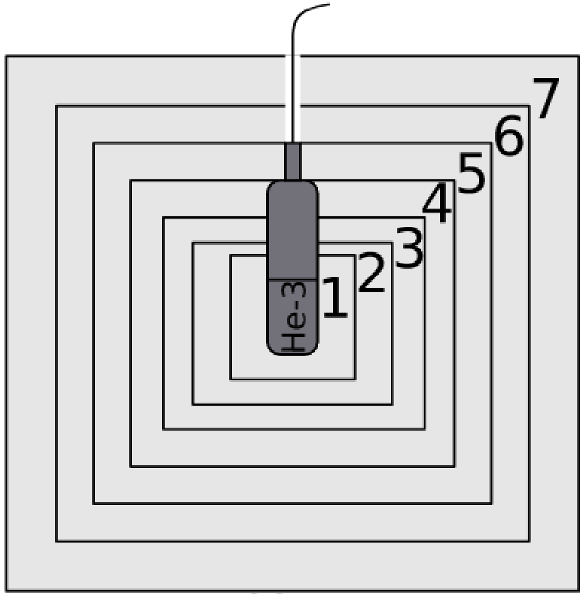
Context

Bonner spheres are a standard for neutron spectrometry but :

- Cumbersome for medical or industrial facilities
- Saturation issues
- Offline analysis

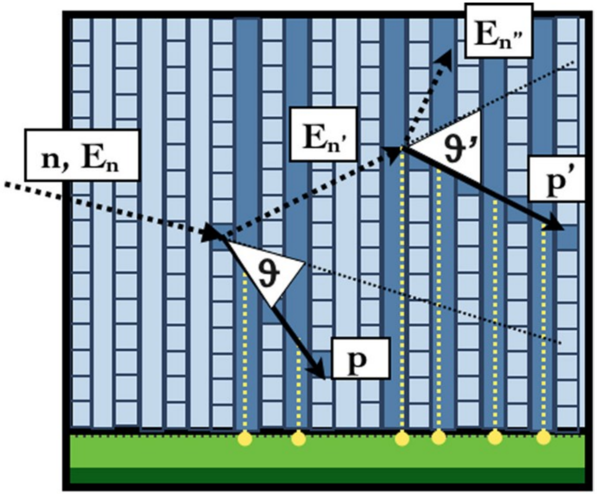
→ Development of dedicated detectors to comply with these constraints

Context



Nested Neutron Spectrometer

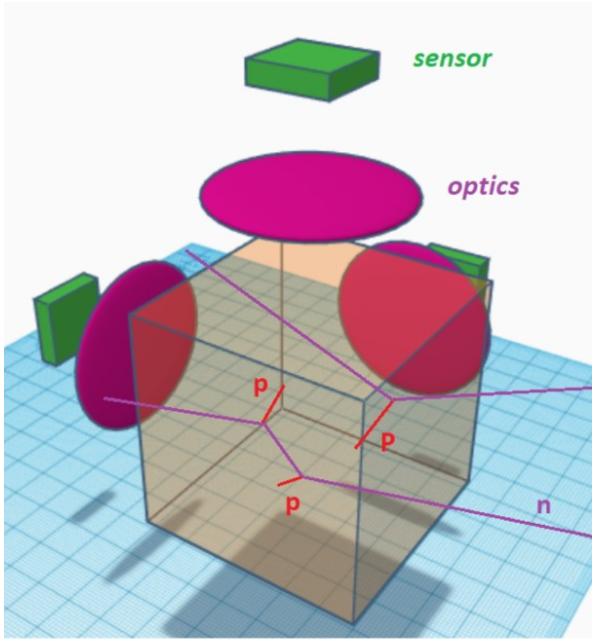
Similar to Bonner Spheres, works in current-mode for signal acquisition



MONDO

20-400 MeV

$\varepsilon \sim 10^{-2}$-10^{-1}



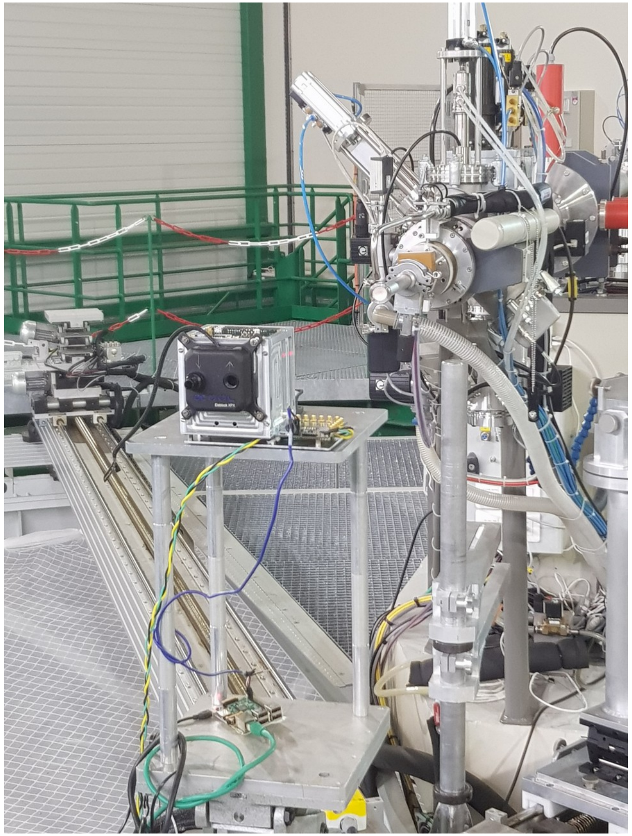
RIPTIDE

Wide energy range, function of scintillator choice + size

$\varepsilon \sim 10^{-1}$

Recoil proton telescope

IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE



Measurements at the AMANDE facility

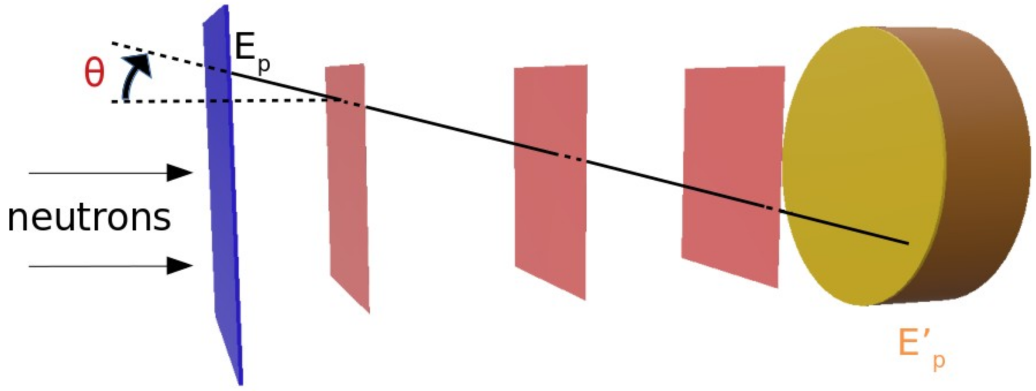
Detector commissioned by the IRSN for metrology of mono-energetic neutron beams from 4 to 30 MeV at their AMANDE facility :

- $\sigma/E < 5$ %
- Compactness ($10\times10\times8$ cm^3)
- For 'high' fluxes ($<10^8$ cm^{-2}.s^{-1})
- Real time measurements

Principle

Measurement of the scattering angle + energy of the recoil proton :

$$E_{neutron} = E_{proton}/\cos^2\theta$$

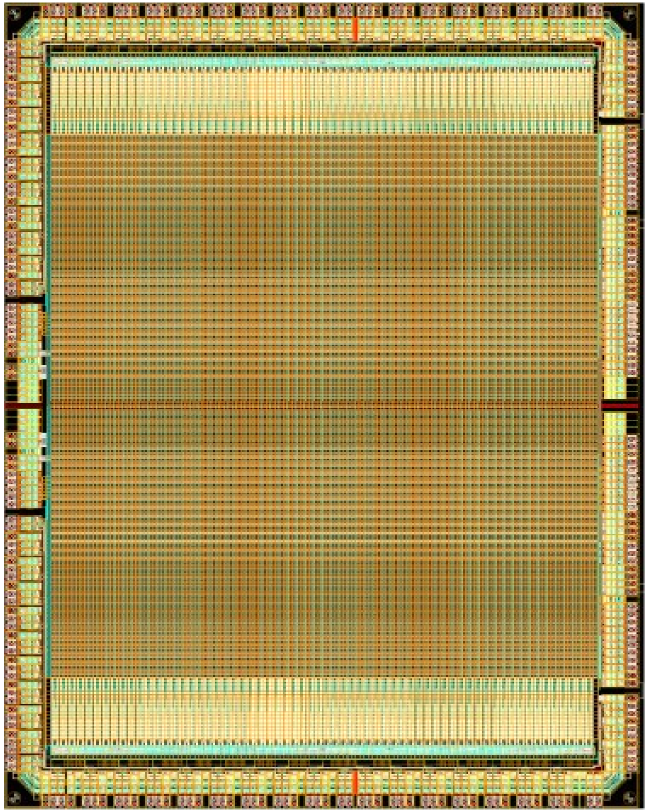


Sketch of the telescope

- $(CH_2)_n$ converter
- 3 FastPixN (pixelated CMOS)
- Si(Li) diode 3 mm thick
- Another thin diode for background elimination

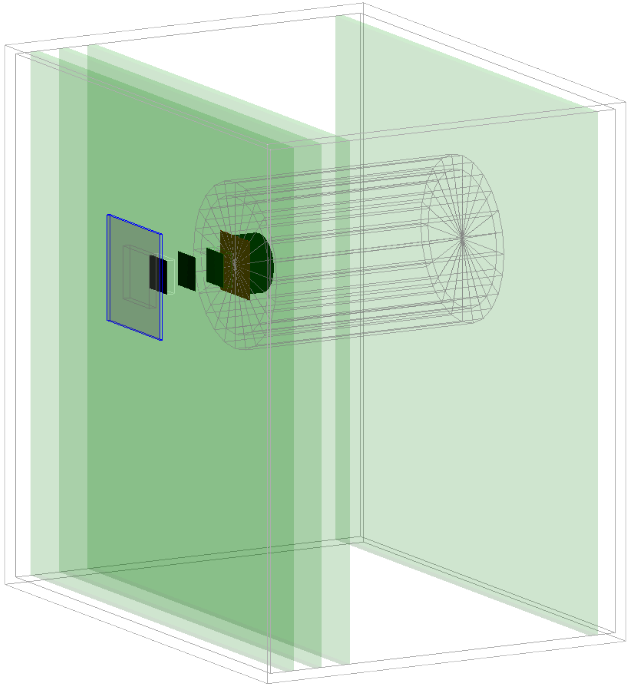
FastPixN CMOS sensors

- Pixel pitch of 50 µm → negligible $(\sigma_\theta)_{pixel}$
- 50 µm thick – protons down to 4 MeV and up to 30 MeV
- 4 bits flash ADC → 15 channels for various proton energies deposit (10 - 200 keV/pixel)
- A frame every 12 µs : up to ~10^4 protons/s (~10^8 neutrons/s)



128×128 pixelated CMOS

Simulation & analysis

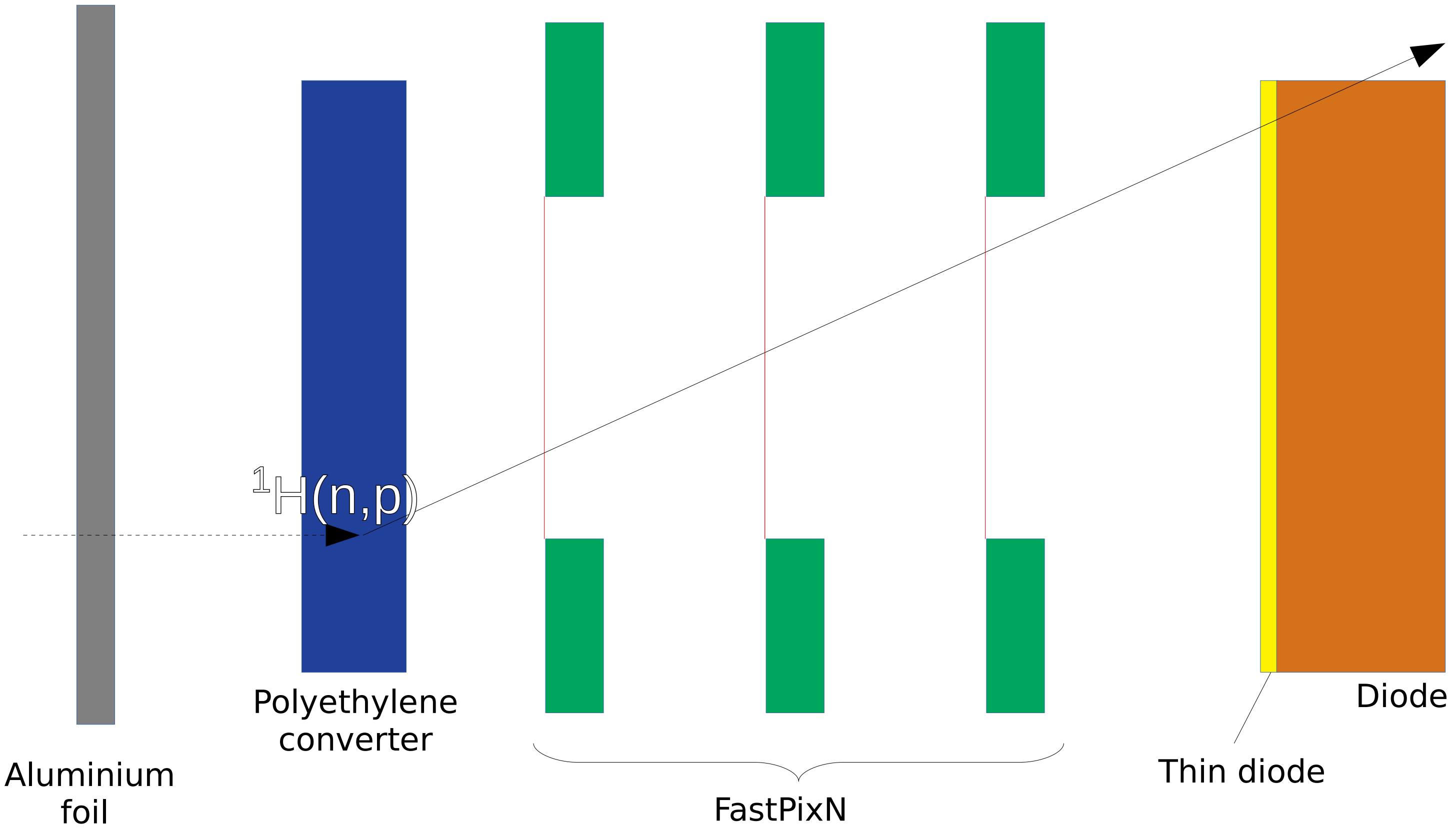


GEANT4 simulation of the whole detector

Geant4 (CERN) simulation of the detector :

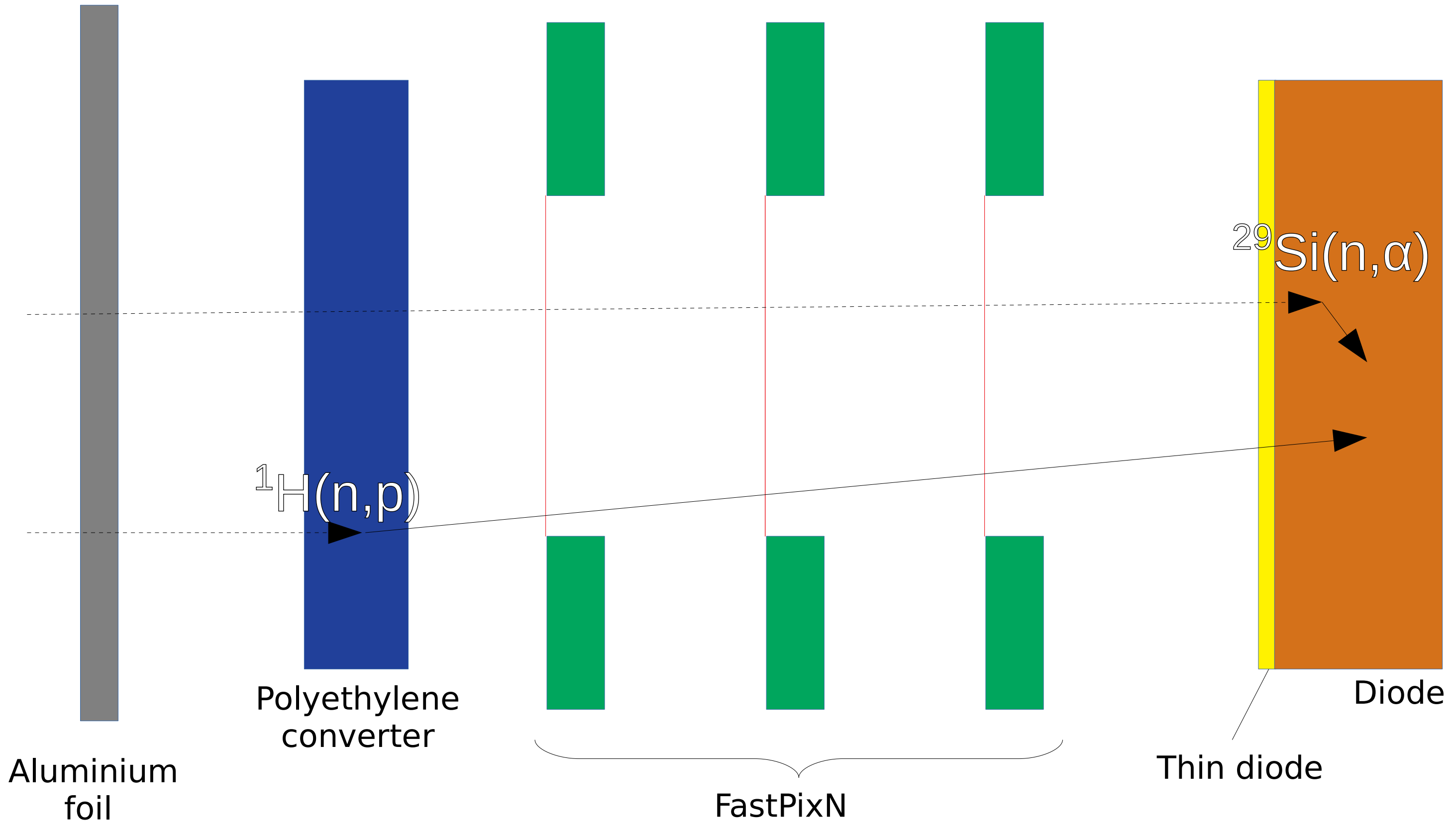
- Verification of the energy reconstruction algorithm
- Understand the origin and intensity of different **background sources**
- Performances estimation (**efficiency**, **background rejection**, impact of neutron flux, **expected resolution**, etc.)

Background elimination



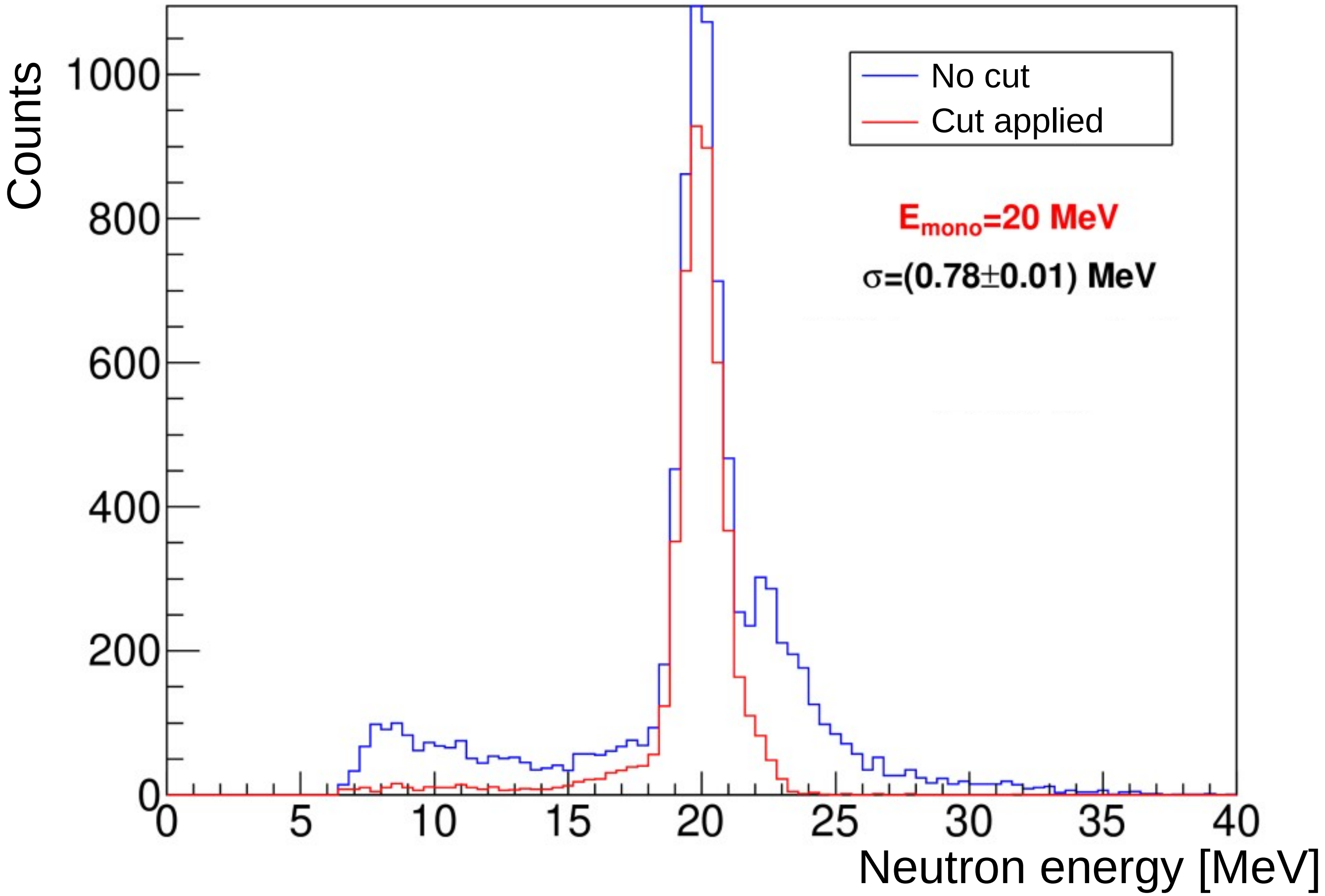
- Proton escape

Background elimination



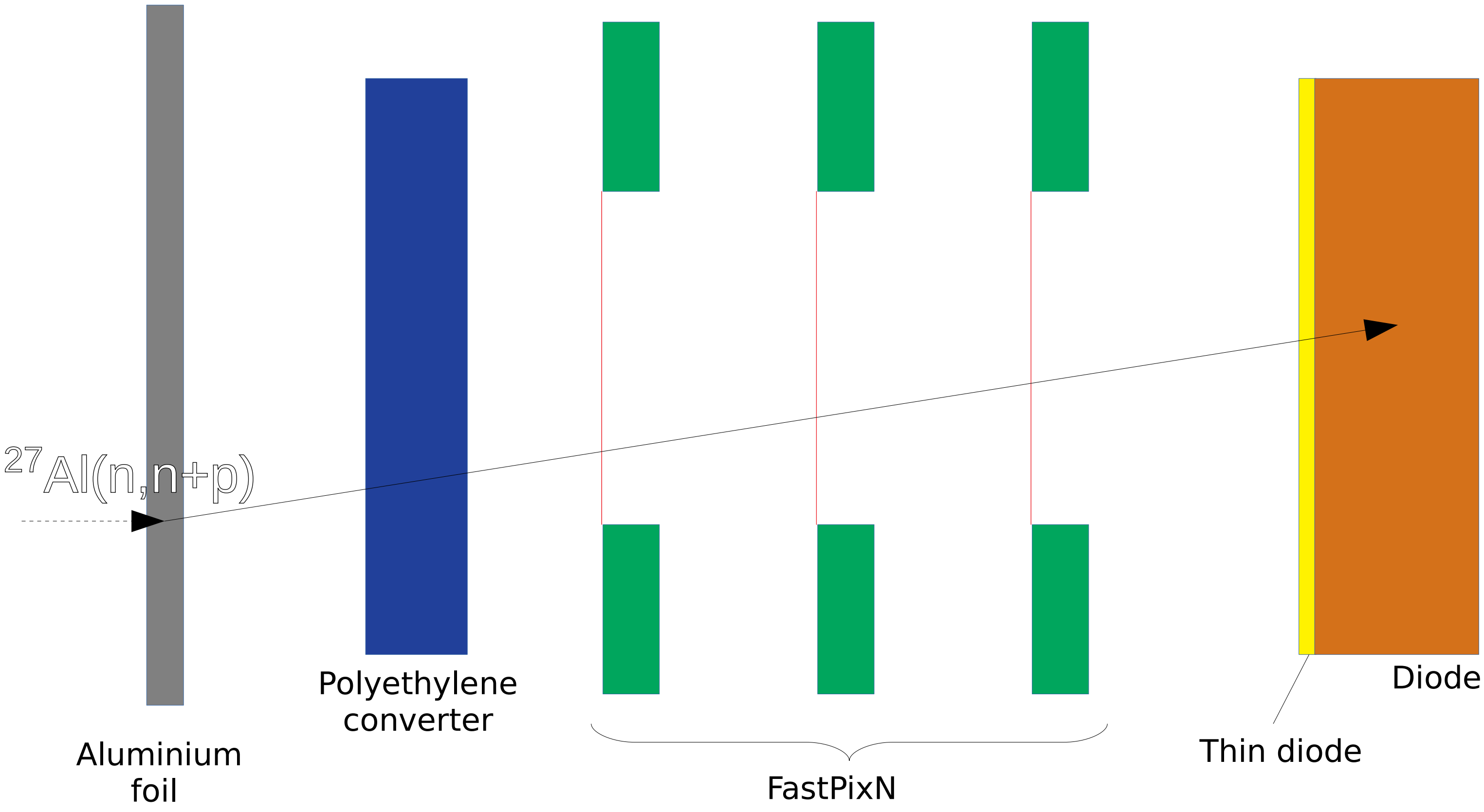
- Proton escape
- Simultaneous direct hit in the diode
- Both eliminated with a ΔE/E verification

Background elimination



Simulation results at 20 MeV with a 500 µm converter

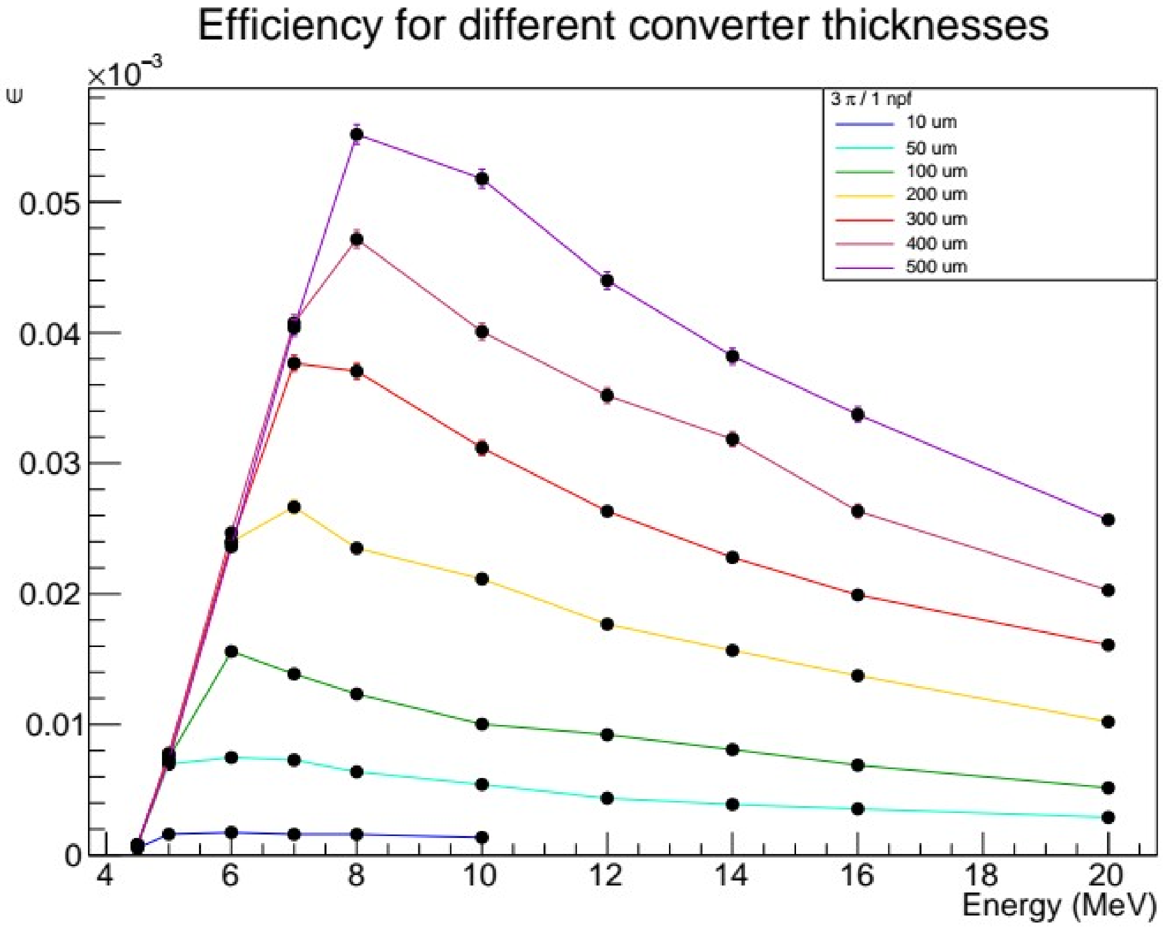
Background elimination



- PCBs
- Diode
- Aluminium
- Converter (^{12}C)

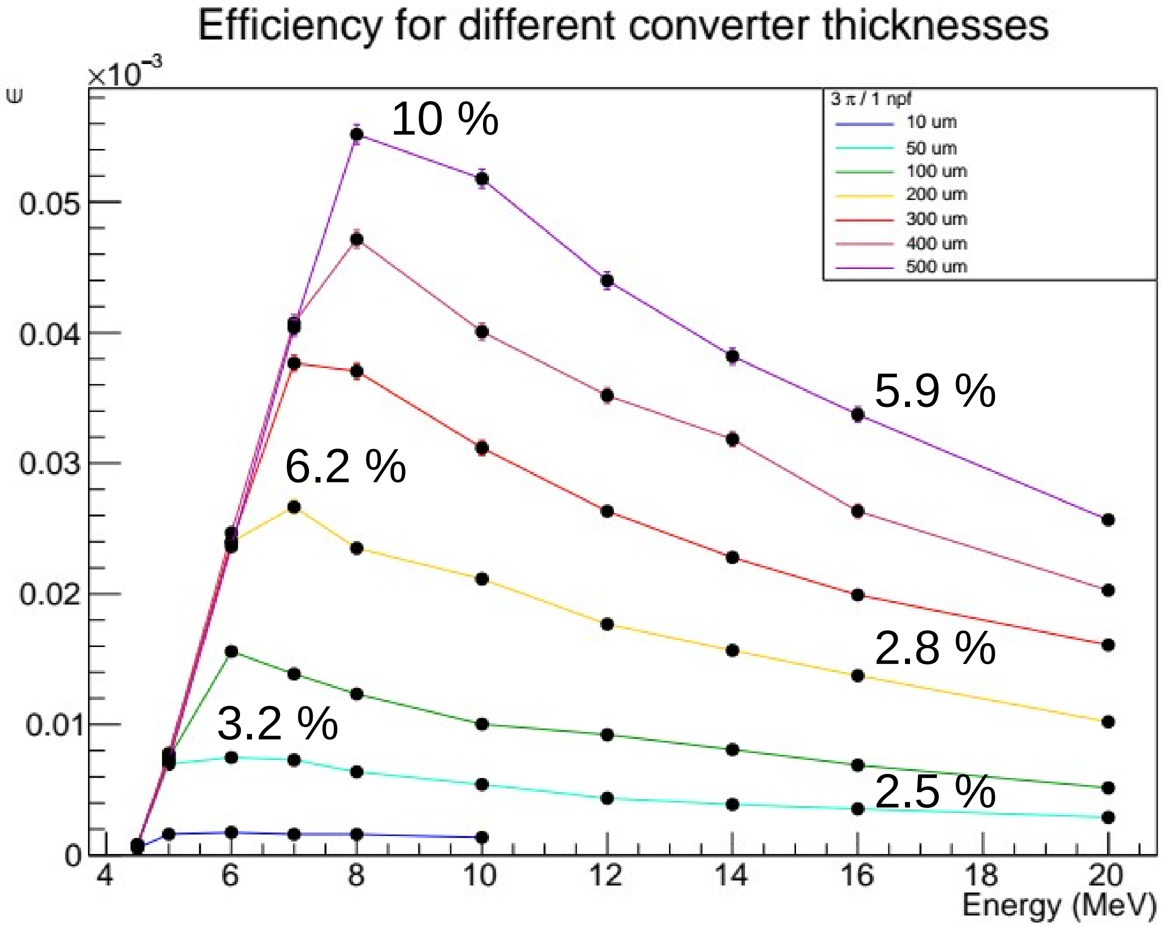
- High scattering
- Additional energy losses

Efficiency



- ε naturally increasing with converter thickness
- $\varepsilon \sim 10^{-5}$
- Maximum efficiency achievable for each energy
- Resolution worsening with converter thickness

Efficiency



- ε naturally increasing with converter thickness
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- Resolution worsening with converter thickness

Neutron energy resolution

$$E_n = E_p / cos^2\theta$$

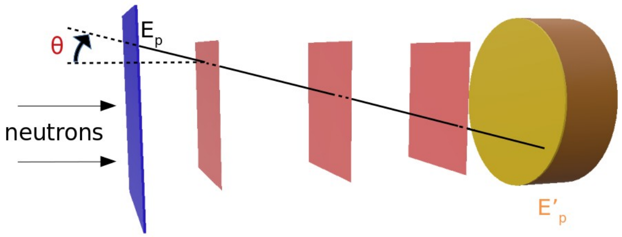
$$(\frac{\sigma_{E_n}}{E_n})^2 = (\frac{\sigma_{E_p}}{E_p})^2 + 4 \cdot tan^2\theta \cdot \sigma_\theta^2 + \frac{4 \cdot tan\theta}{E_p} \cdot \sigma_{E_p} \cdot \sigma_\theta \cdot \rho_{E_p,\theta}$$

Always present, even at θ=0

Led by angular uncertainty

Neutron energy resolution : proton energy

The energy measured by the diode is corrected by energy losses in the converter and the sensors : sources of uncertainties



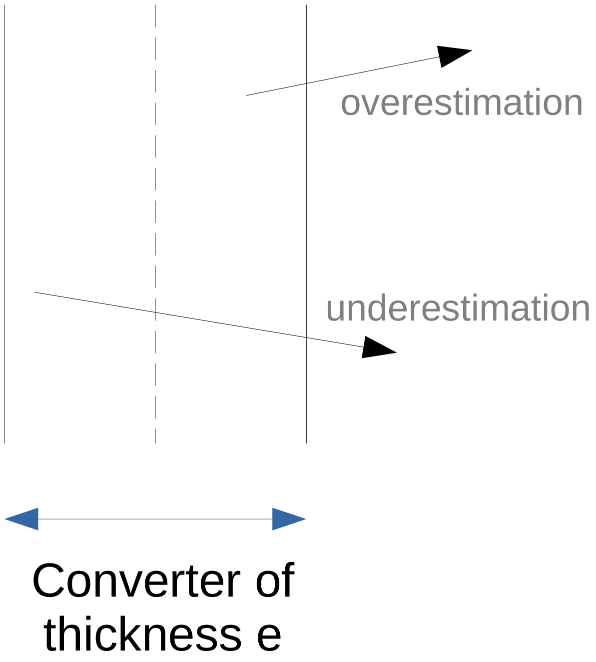
$$\sigma^2(E_p) = \sigma^2_{diode} + \sigma^2_{CMOS} + \sigma^2_{converter}$$

Diode energy resolution (σ^2_{diode})

Uncertainties on the average energy loss hypothesis ($\sigma^2_{CMOS} + \sigma^2_{converter}$)

Neutron energy resolution : proton energy

$$\sigma^2(E_p) = \sigma^2_{diode} + \sigma^2_{CMOS} + \sigma^2_{converter}$$



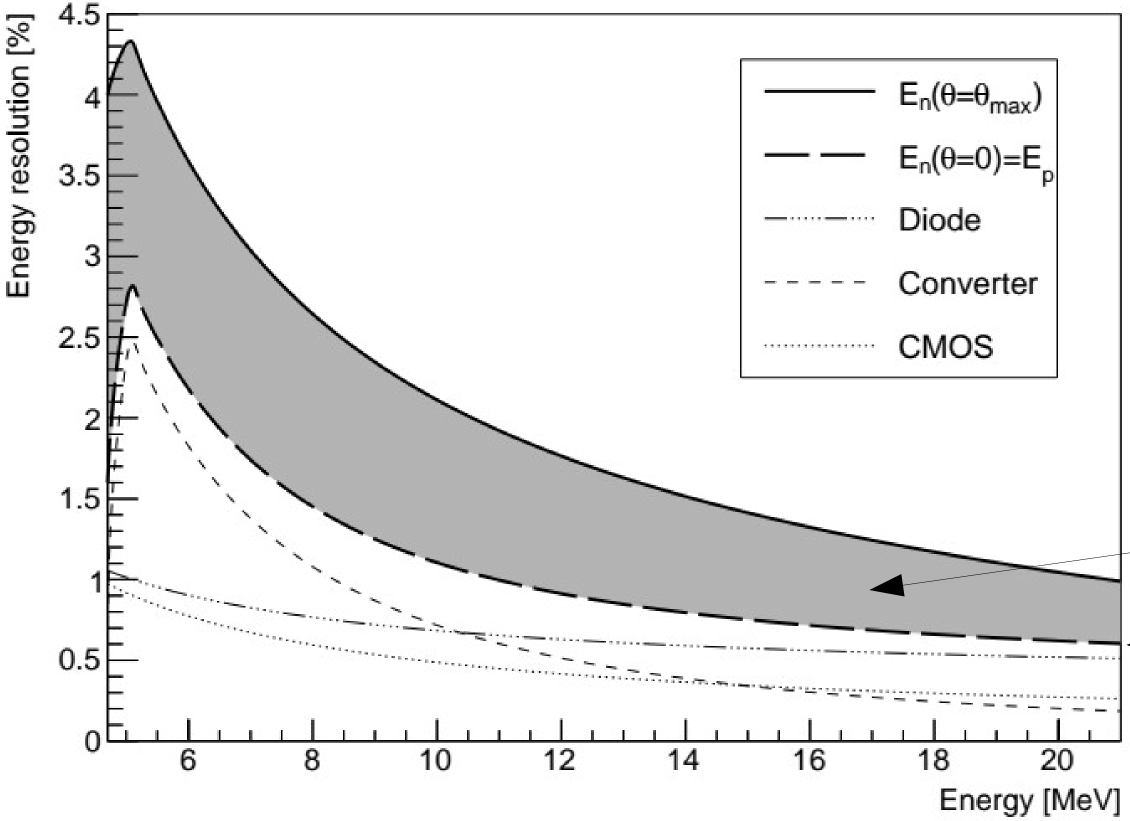
Hypothesis : neutrons are generated at e/2

→ scattering after e/2 : overestimation

→ scattering before e/2 : underestimation

Thicker converter means better efficiency but worse resolution

Neutron energy resolution : conclusion



Neutron energy resolution with d_{conv}= 50 µm

- Uncertainty dominated by the converter at low energies
- Dominated by the diode resolution at higher energies

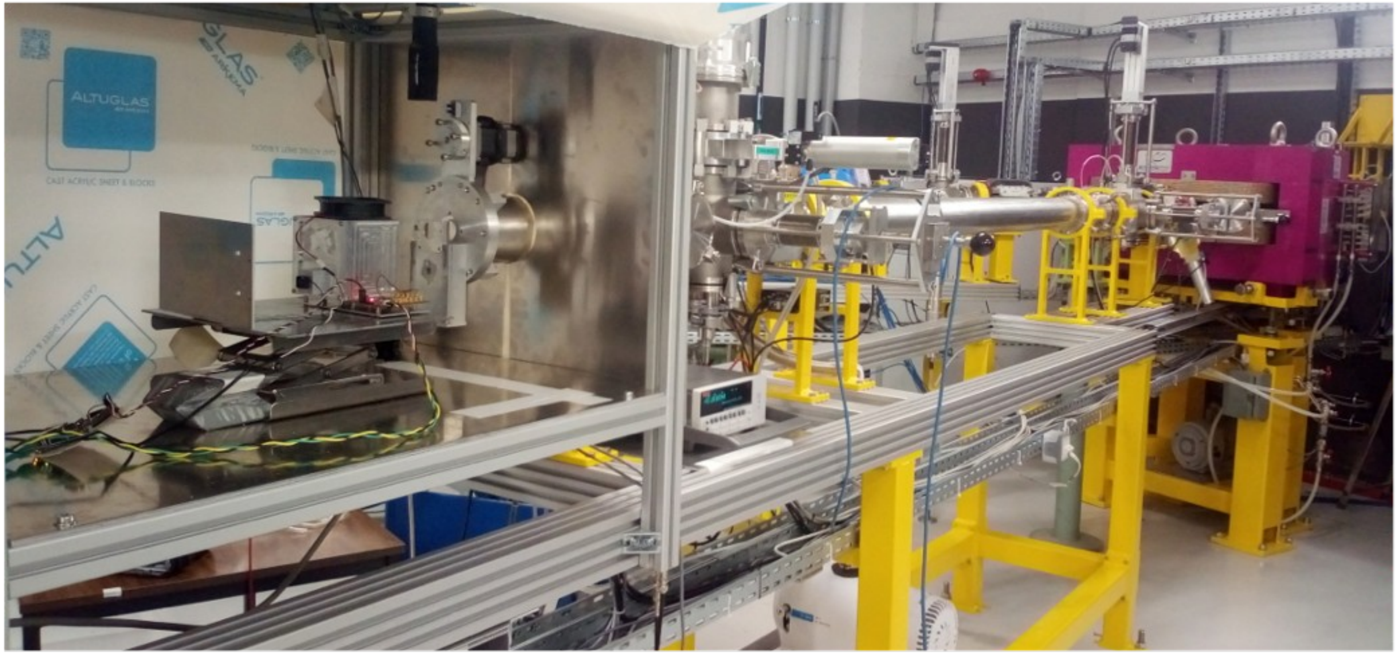
angular dependency from 0° (best) to ~37° (worst)

best achievable resolution

$$\sigma^2(E_p) = \sigma^2_{diode} + \sigma^2_{CMOS} + \sigma^2_{converter}$$

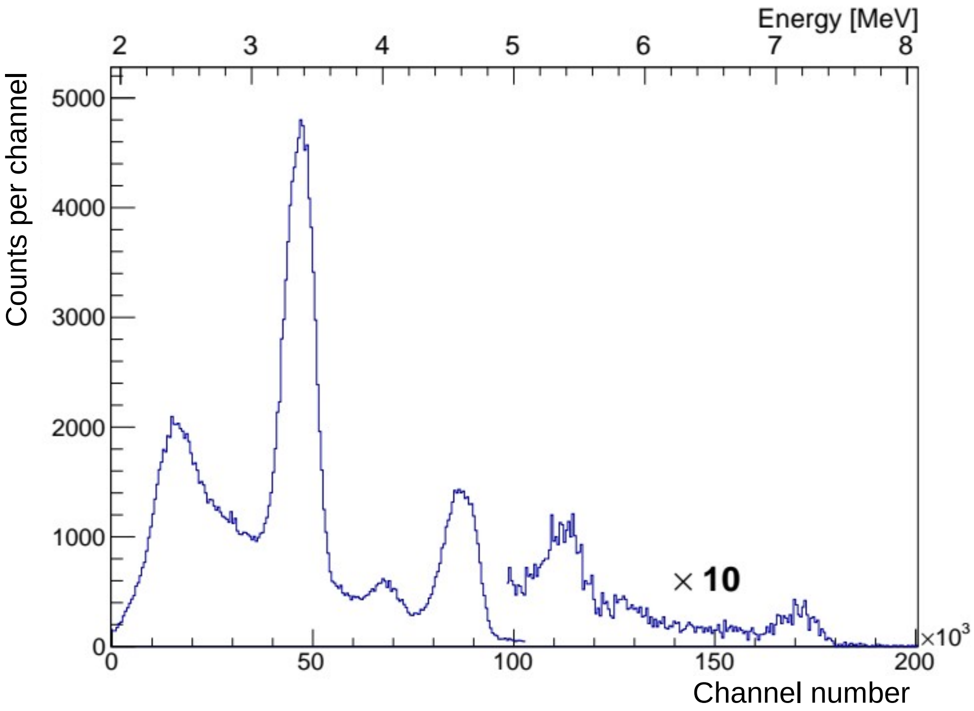
Diode calibration

The diode calibration has to be as precise as possible BUT sensitive to temperature variations and radiation damages over time → it has to be reassessed regularly

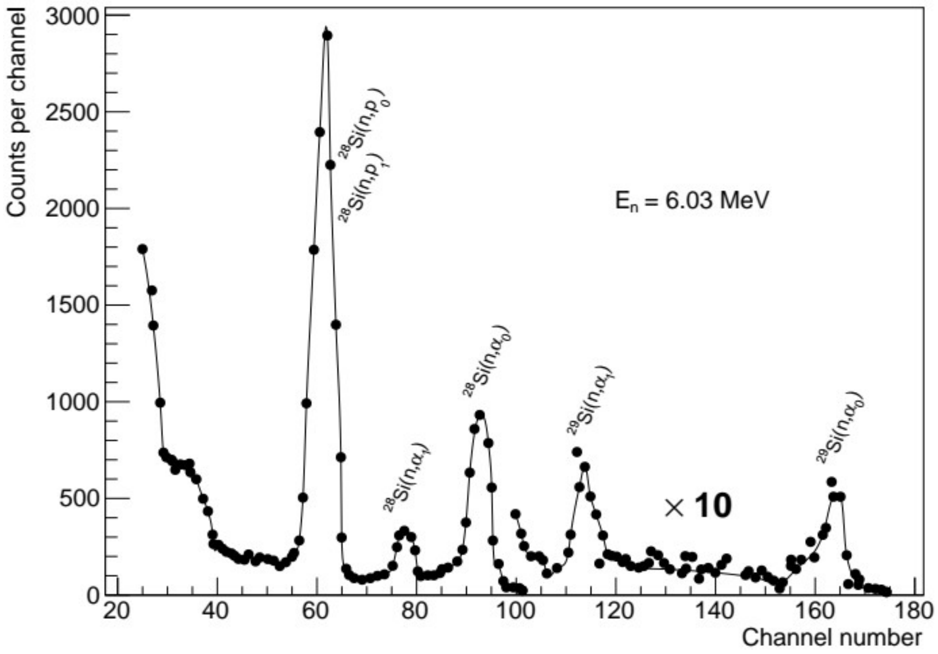


CyRCE cyclotron (Strasbourg-France) up to 24 MeV

Diode calibration

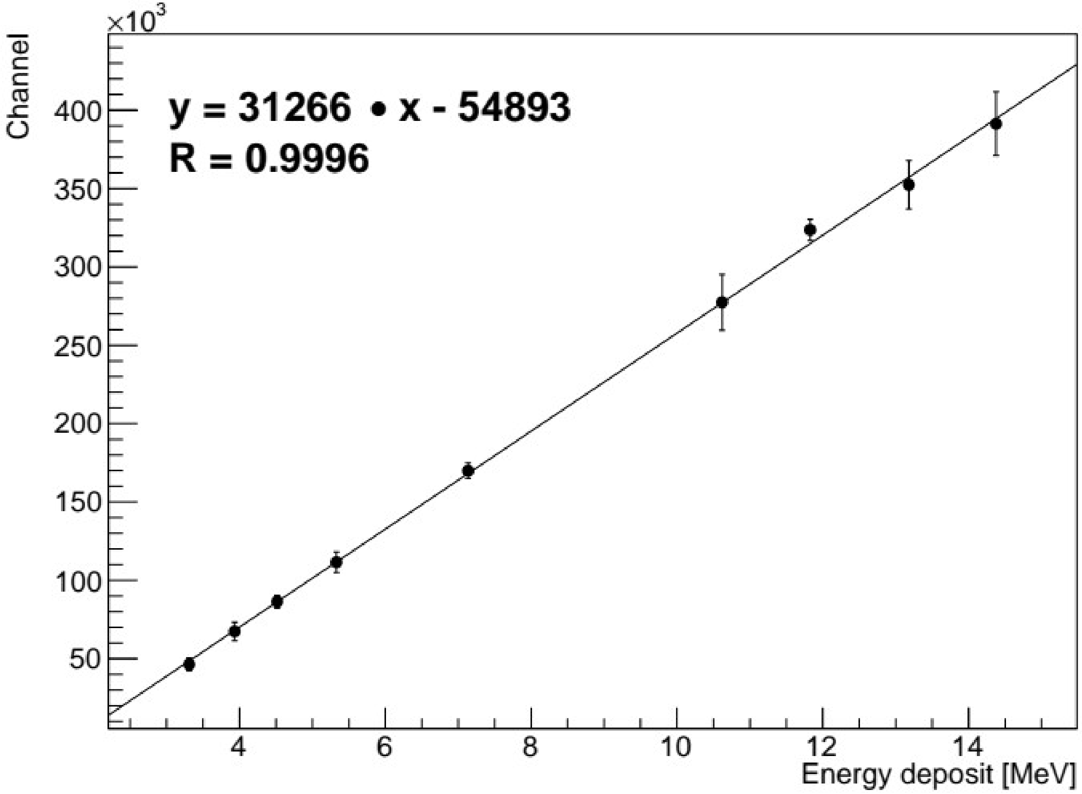


Raw diode spectrum at AMANDE for E_n = 7.17 MeV



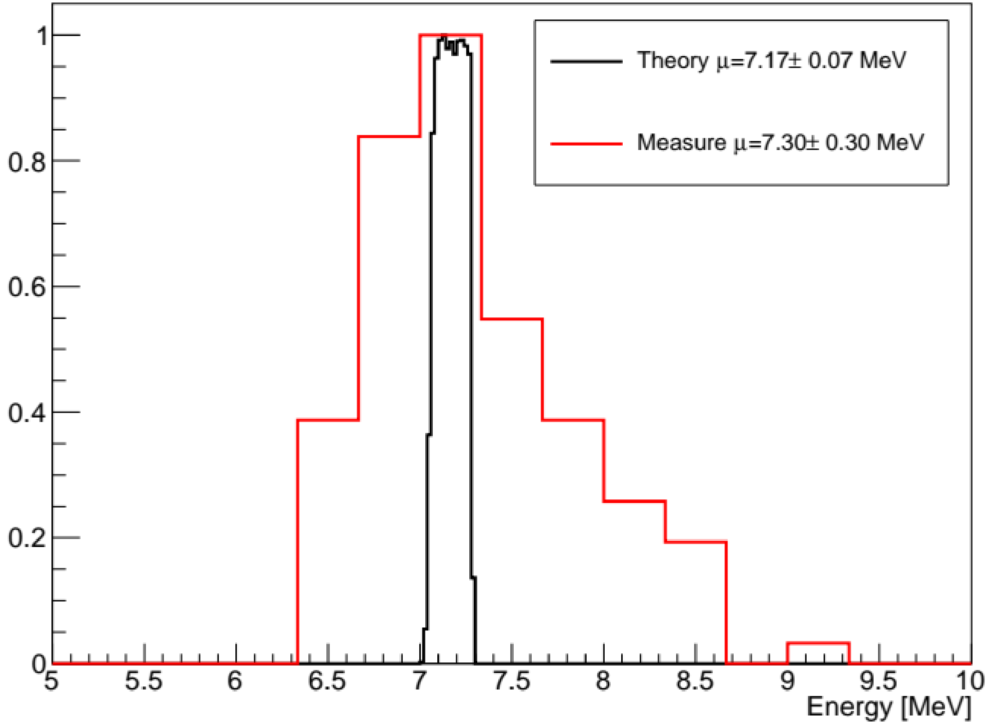
Raw diode spectrum at E_n = 6.03 MeV reproduced from B. Mainsbridge et al., 1963

Diode calibration



Diode calibration made from neutron measurements at the AMANDE facility

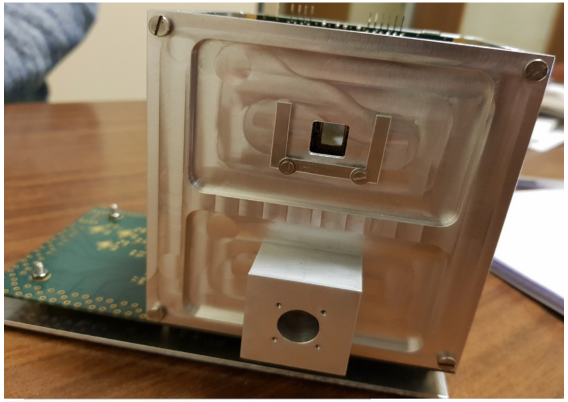
Diode calibration

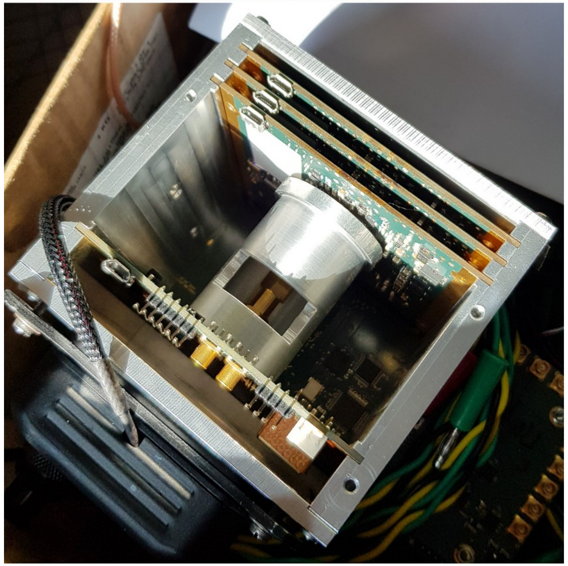


Theoritical and reconstructed spectra of 7.17 MeV at AMANDE, normalized to the maximum of each spectrum

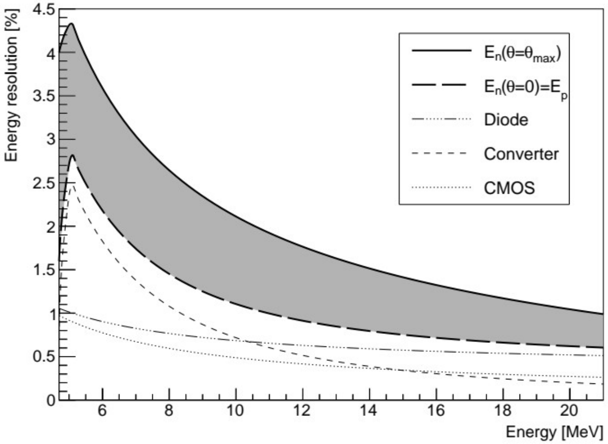
- Spectrum peaked on the right energy (mean value slightly overestimated)
- σ/E = 4.2 % (thick converter)

Conclusion and prospects

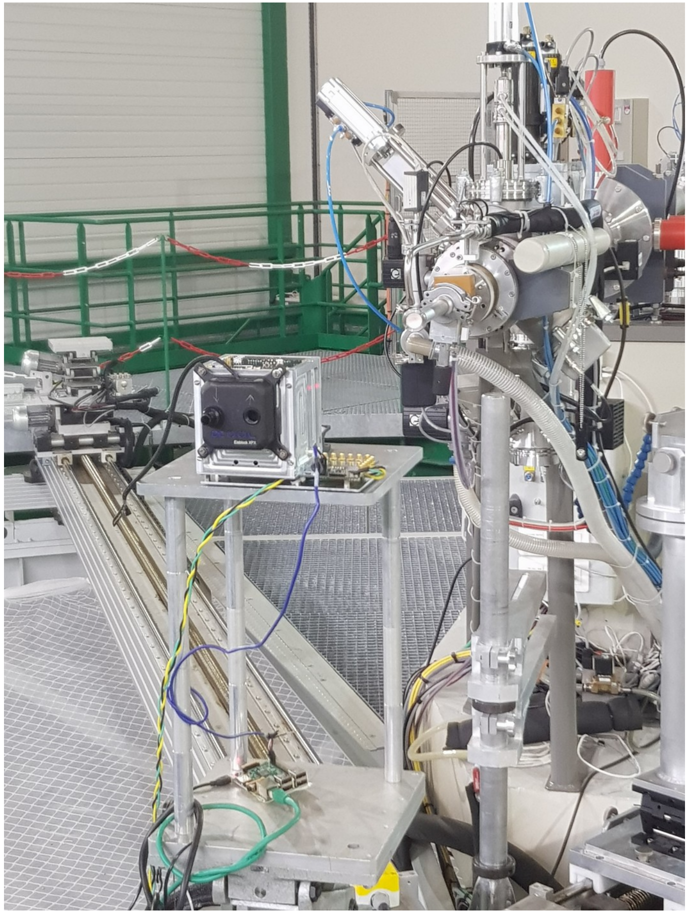




- Development of a compact real-time neutron spectrometer
- σ < 5 %
- Simulated performances



Conclusion and prospects



- Test of in-situ diode calibration method using mono-energetic neutron beam
- First reconstructed neutron spectrum

Conclusion and prospects

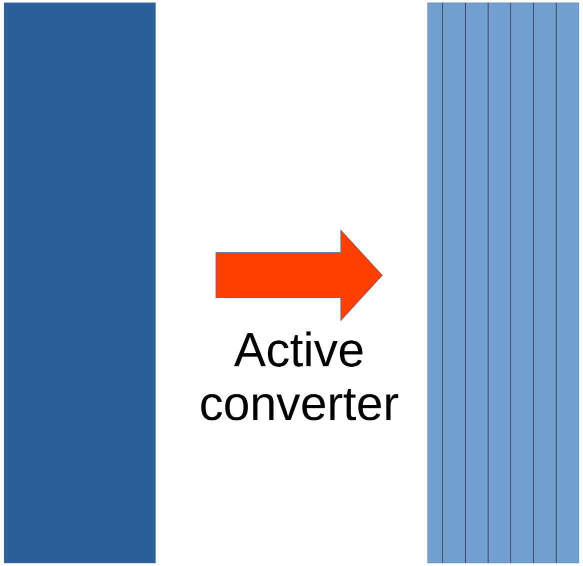
- Future experiments :

CAL protontherapy center (Nice, France)

Aérial-FEERIX (Strasbourg, France)

Conclusion and prospects

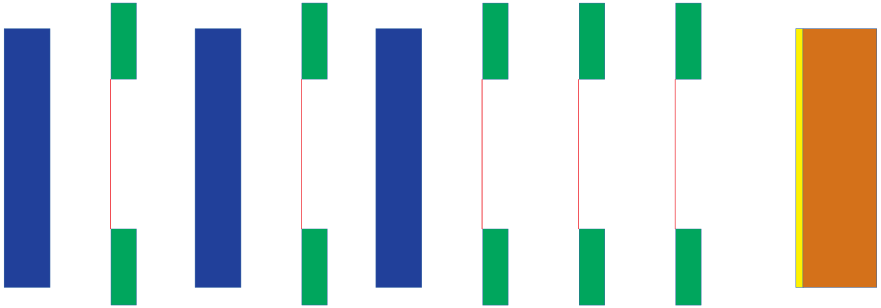
Improvements for future versions :



$(CH_2)_n$ replacement by a stack of thin plastic scintillators :

→ higher efficiency and better resolution

→ improved background events removal



Stack of converters and CMOS planes :

→ extended energy range

→ but even more background events to manage

Thank you