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Measuring the delayed neutrons of the thermal induced fission of ^{235}U, ^{233}U and ^{239}Pu

Benoit Geslot (CEA) on behalf of the ALDEN collaboration

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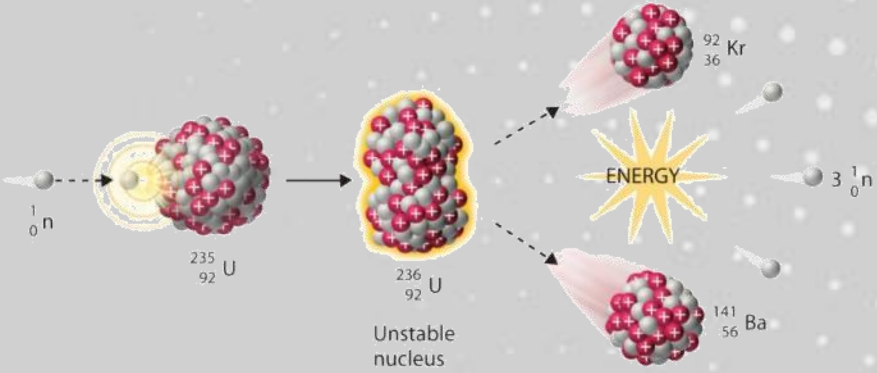
ANIMMA Conference, 24th June 2021

1. Why Measure Delayed Neutrons ?
   - What are “delayed” neutrons ?
   - Some nuclear reactor physics
   - Principle of measuring delayed neutrons
2. New Experiments on PF1b Cold Neutron Beam (@ILL)
   - Detection system and setup
   - Data acquisition and filtering
3. Data Analysis
   - Data reduction
   - Dead time correction
4. Results and Discussion
   - Results for ^{235}U in June 2019
   - Results for ^{239}Pu in March 2021 (preliminary)
5. Summary and Outlooks



1. Why measure delayed neutrons ?

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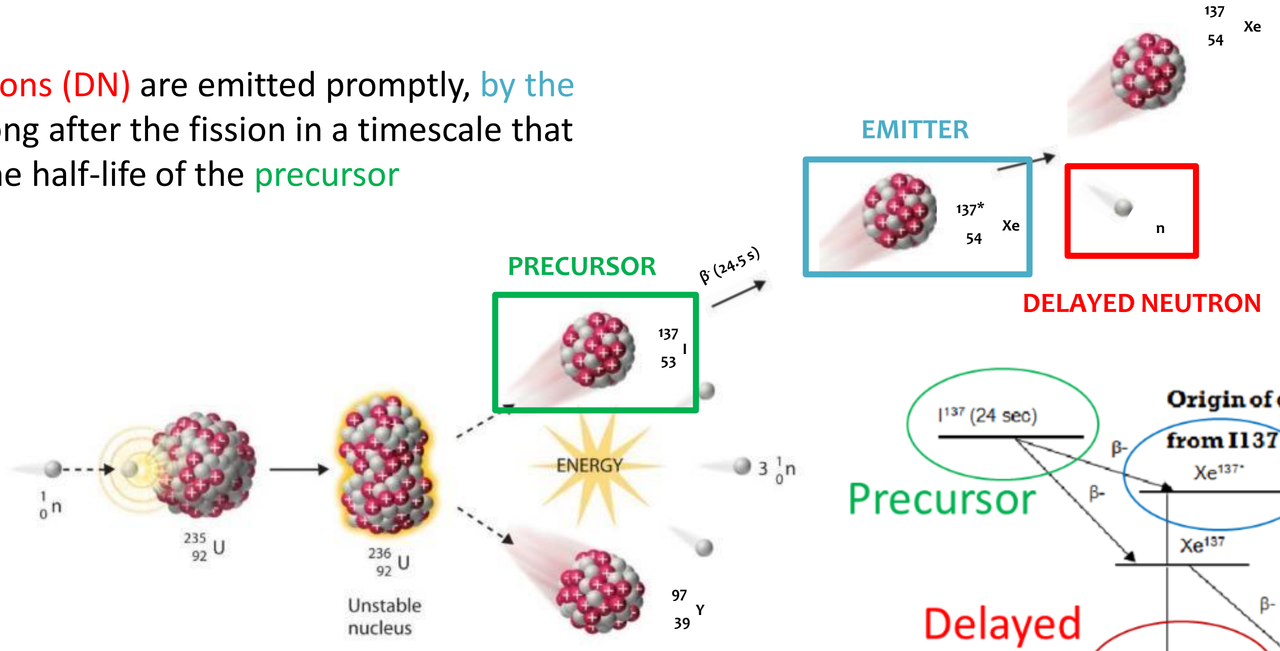
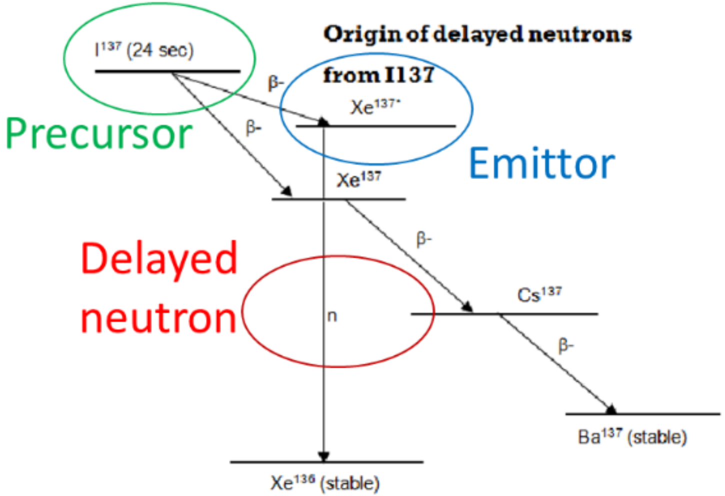
1. Why measure delayed neutrons ?

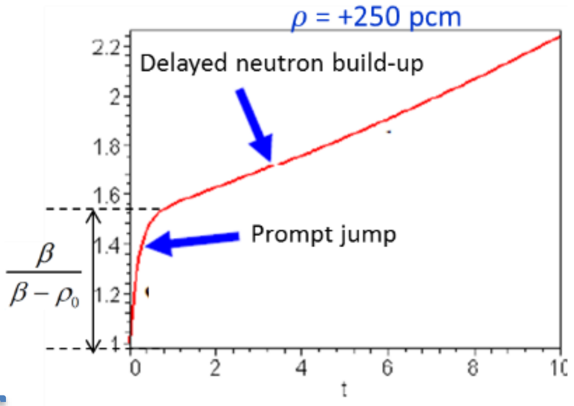
What are delayed neutrons ?

Delayed neutrons (DN) are emitted promptly, by the emittor, but long after the fission in a timescale that depends on the half-life of the precursor





Hundreds of precursors are regrouped into 6 (ENDF) or 8 (JEFF) « families » based on their time constants



The kinetics of nuclear reactors is dominated by delayed neutrons

- Small fraction of the neutron population: $\beta = \nu_d / \nu_{tot} \approx 0.075\ \%$
- Reactivity is a major safety parameter and its prediction uses DN parameters
- Reactors safety margins depend directly on nuclear data uncertainties

$$\rho = \frac{\Lambda}{T} + \beta_{eff} \sum_i \frac{a_i}{1 + \lambda_I T} \approx \beta_{eff} \frac{\overline{T_{1/2}}}{T}$$

σ ≈ 3%

$$\beta_{eff} = \frac{\sum_k \int_0^\infty \Phi^+(E')\,\chi_{d,k}(E')dE' \int_0^\infty \nu_{d,k}(E)\Sigma_{f,k}(E)dE}{\sum_k \int_0^\infty \Phi^+(E')\,\chi_{t,k}(E')dE' \int_0^\infty \nu_{t,k}(E)\Sigma_{f,k}(E)dE}$$

σ ≈ 3%

$$\overline{T_{1/2}} = \sum_i \frac{a_i}{\lambda_i}$$

$$\overline{T_{1/2}} \approx 9\ \text{s}$$

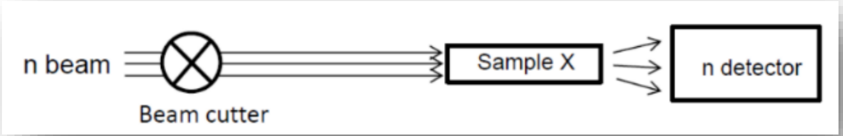
Principle of measuring DN

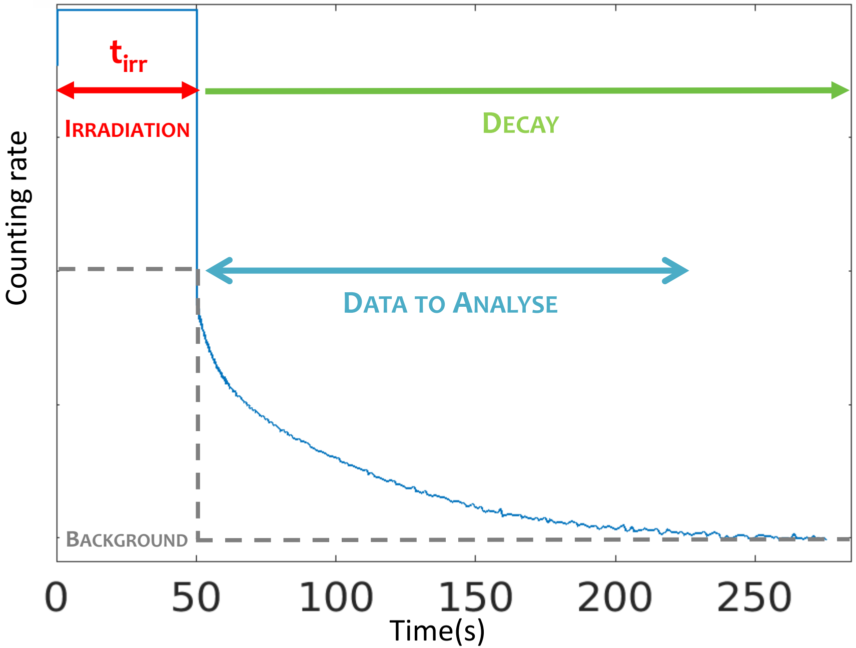
Detection system in 3 parts

- An efficient neutron detector
- A fissile sample
- A fast beam shutter

What needs to be optimized

- The sample's fission rate
- The efficiency vs. energy of DN
- The background (beam on & beam off)





Analytical models

$$C_i = F \cdot \nu_p \cdot \epsilon_p + F \cdot \nu_d \cdot \sum_{i=1}^{8} \epsilon_{d,i} \cdot a_i \cdot \left(1 - e^{-\lambda_i \cdot t}\right)$$

$$C_d = F \cdot \nu_d \sum \epsilon_{d,i} \cdot a_i \cdot \left(1 - e^{-\lambda_i \cdot t_{irr}}\right) \cdot e^{-\lambda_i \cdot t}$$

DN yield per fission

$(t_{irr} \rightarrow \infty \ \& \ t \rightarrow 0)$

$$C_i = F \cdot \nu_p \cdot \epsilon_p + F \cdot \nu_d \cdot \sum_{i=1}^{8} \epsilon_{d,i} \cdot a_i$$

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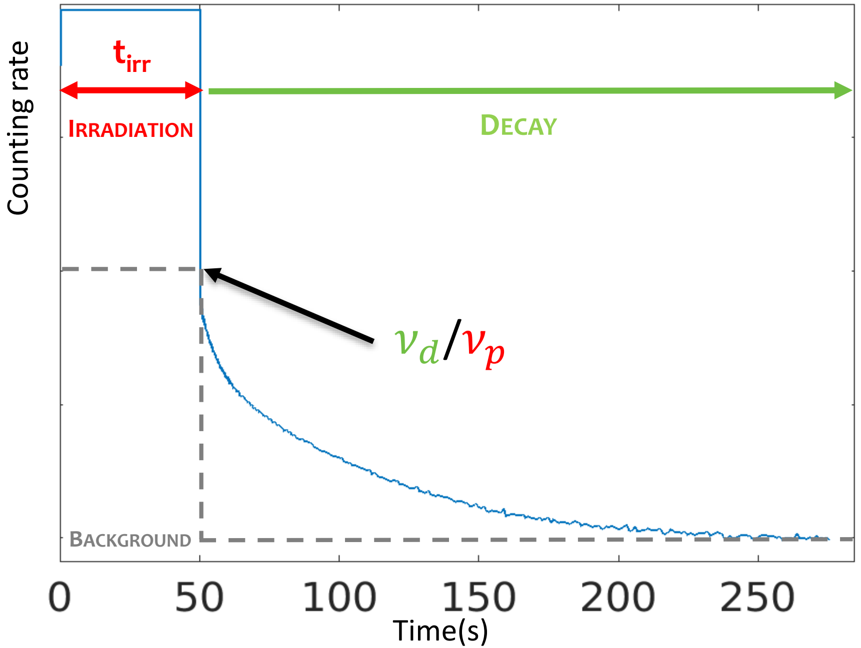

2. Experiments on PF1b cold neutron beam (ILL)

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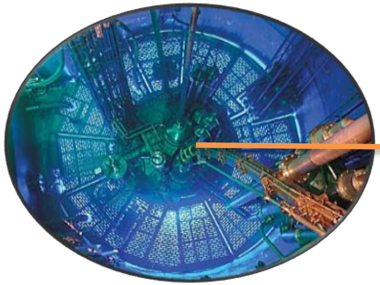
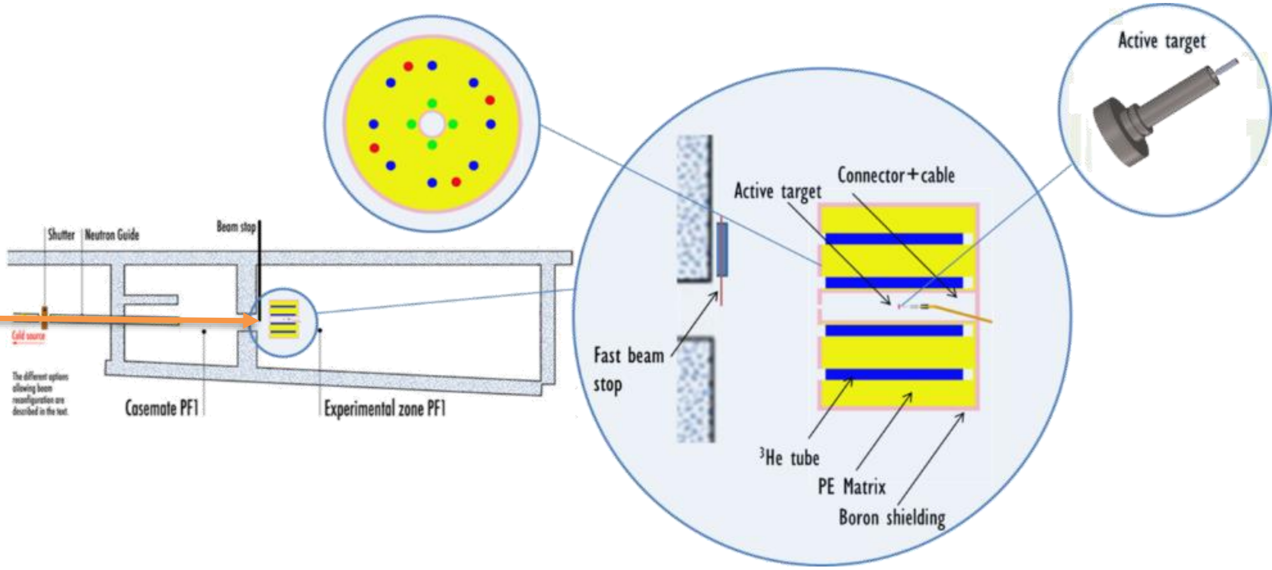
PF1b « cold » neutron beam

- Neutron energy ~5 meV => $\sigma_f(^{235}U)$ = 1350 barns
- Flux max : 2 10^{10} n/cm²/s : little amount of fissile material required
- With a fast beam shutter => measurement of short-lived DN



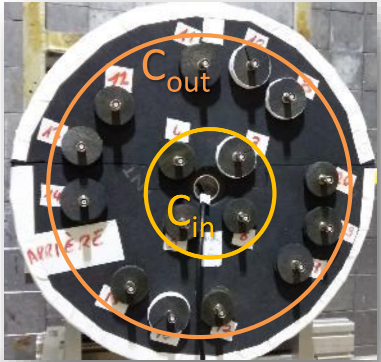
HFR (P=65 MW_{th})



Detection system and setup

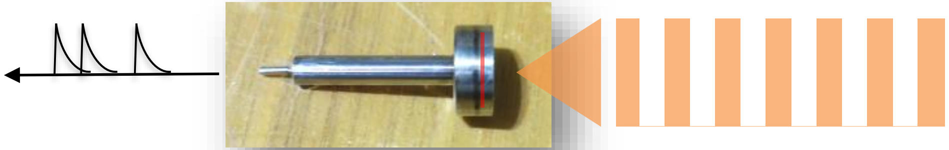
Detection system

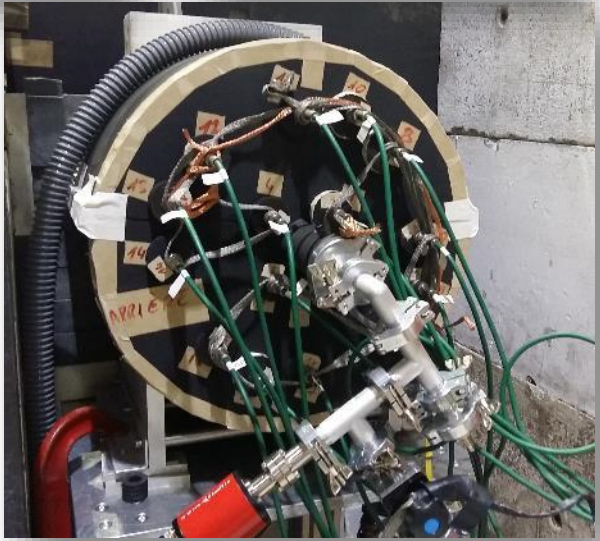
- 2 rings of ^{3}He proportional counters in a block of PEHD
- Shielding to absorb scattering neutrons
- Central hole for the fissile target
- Airtight tube to monitor any activity release



Fissile target

- A parallel plate miniature fission chamber
- Allow to record the instant fission rate





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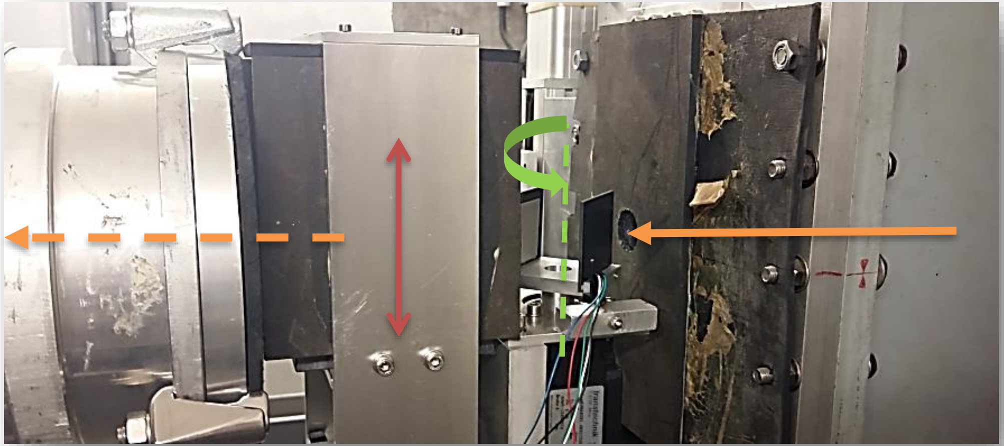
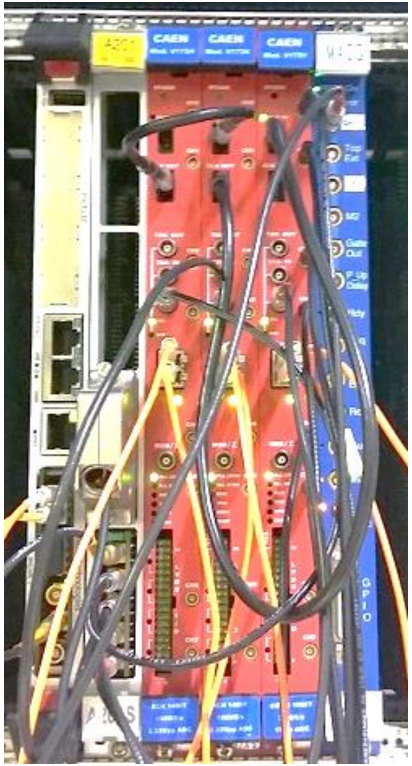


Beam shutters

- One rotating double screen (B4C/Cd)
- One axial polyethylene with boron

2. Experiments on PF1b cold neutron beam (ILL)

Data acquisition and filtering



Front end amplifiers

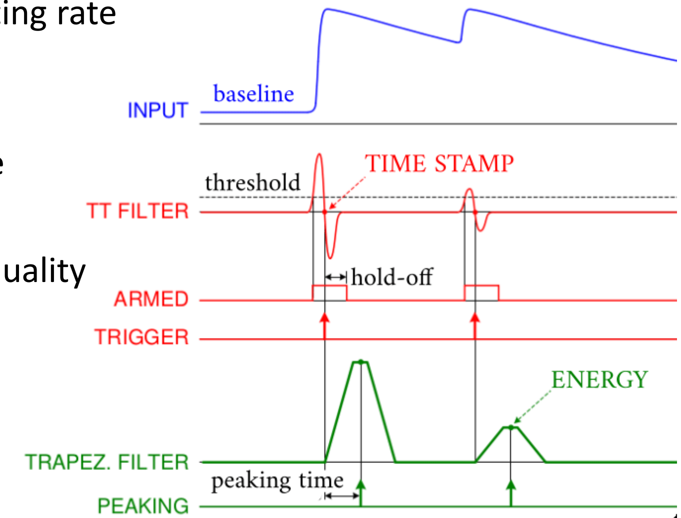
- 16 channels charge preamplifiers (ILL) => ^{3}He PCs
- Amplifier + Discriminator (Canberra) => Fission chamber

CAEN read out (VME)

- Two V1724 digitizers (8 ch., 100 MHz fast ADC, 14bits) => ^{3}He PCs signals
- One V1751 PSD acquisition (4 ch. 2 GB/s, 10 bits) => Shutters monitoring
- One histograming card => Fission chamber counting rate

Pulses processing algorithm (DPP-PHA)

- Input signal => get arrival time + pulse amplitude
- Filter noise, trigger and shape pulses
- Trigger Threshold (TT) has a big impact on data quality (SNR, dead time)



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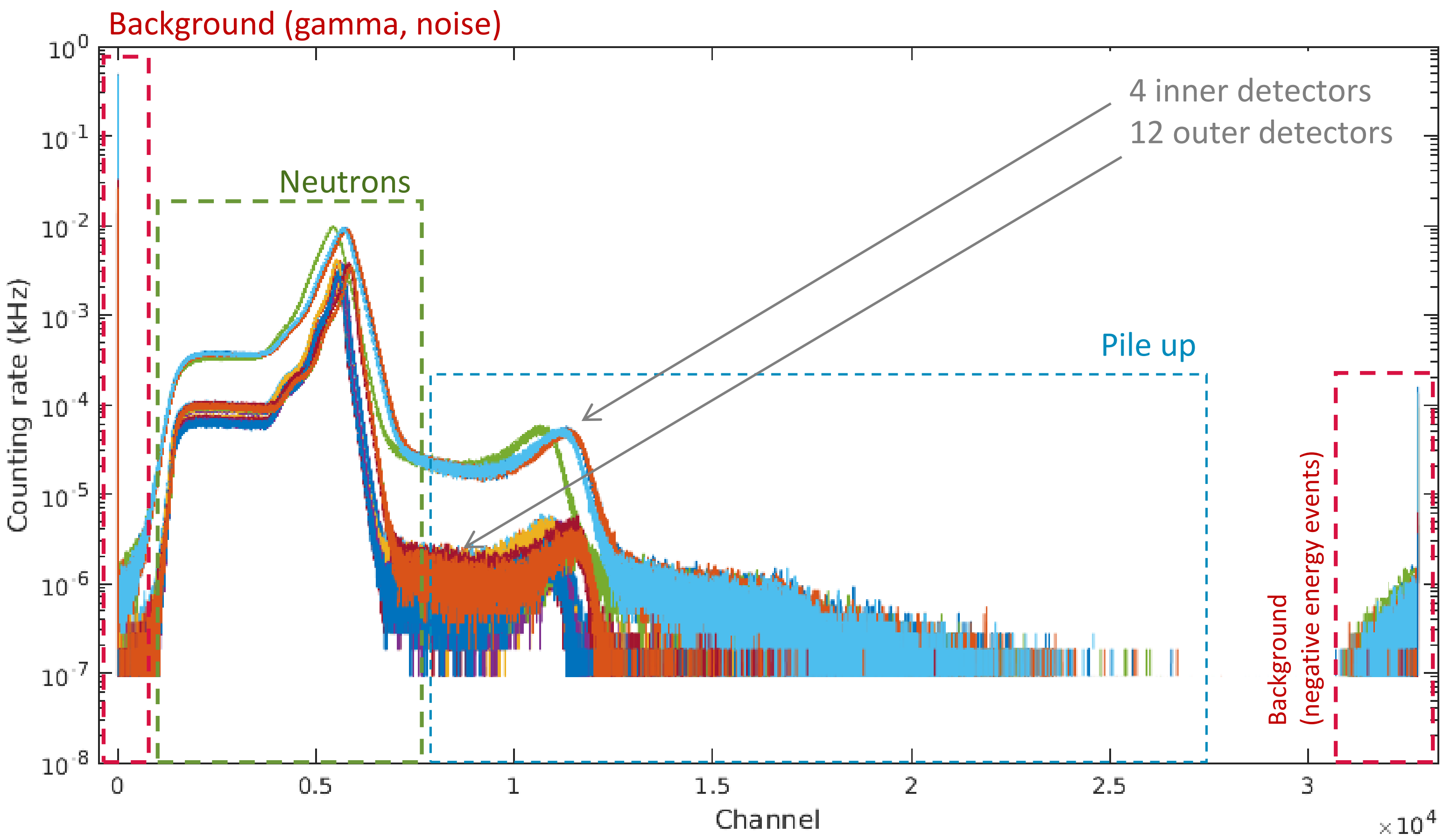

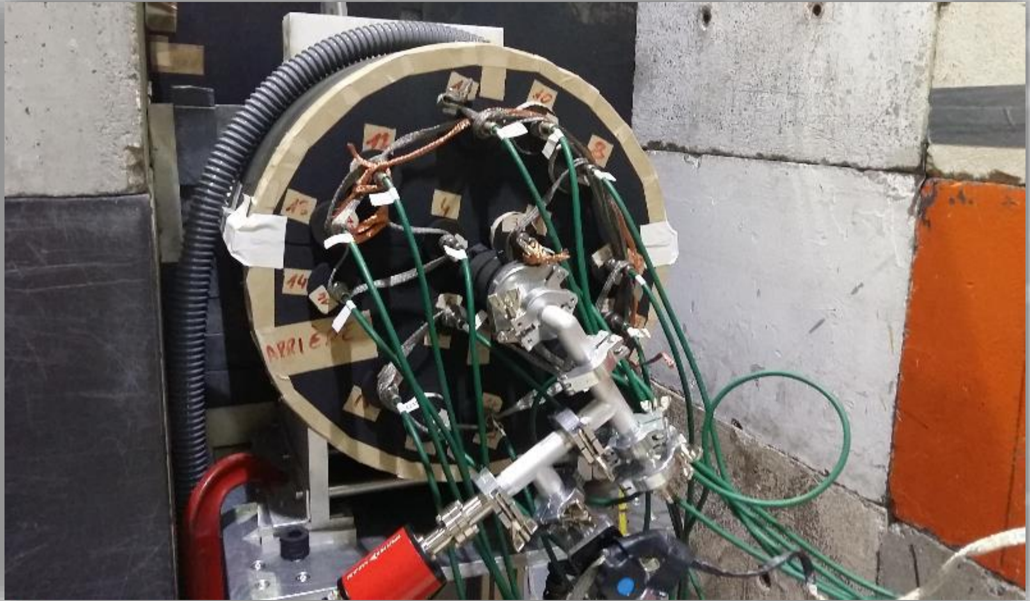

3. Data Analysis

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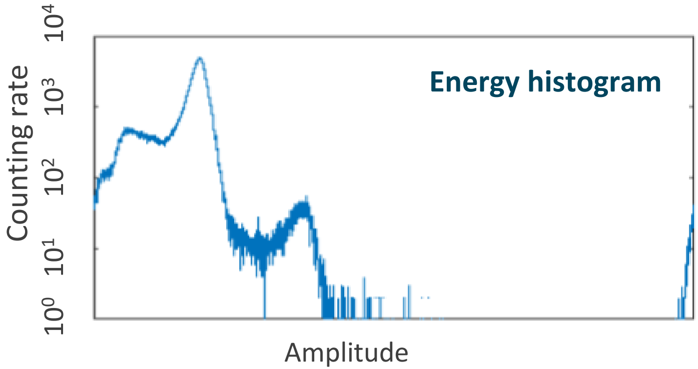
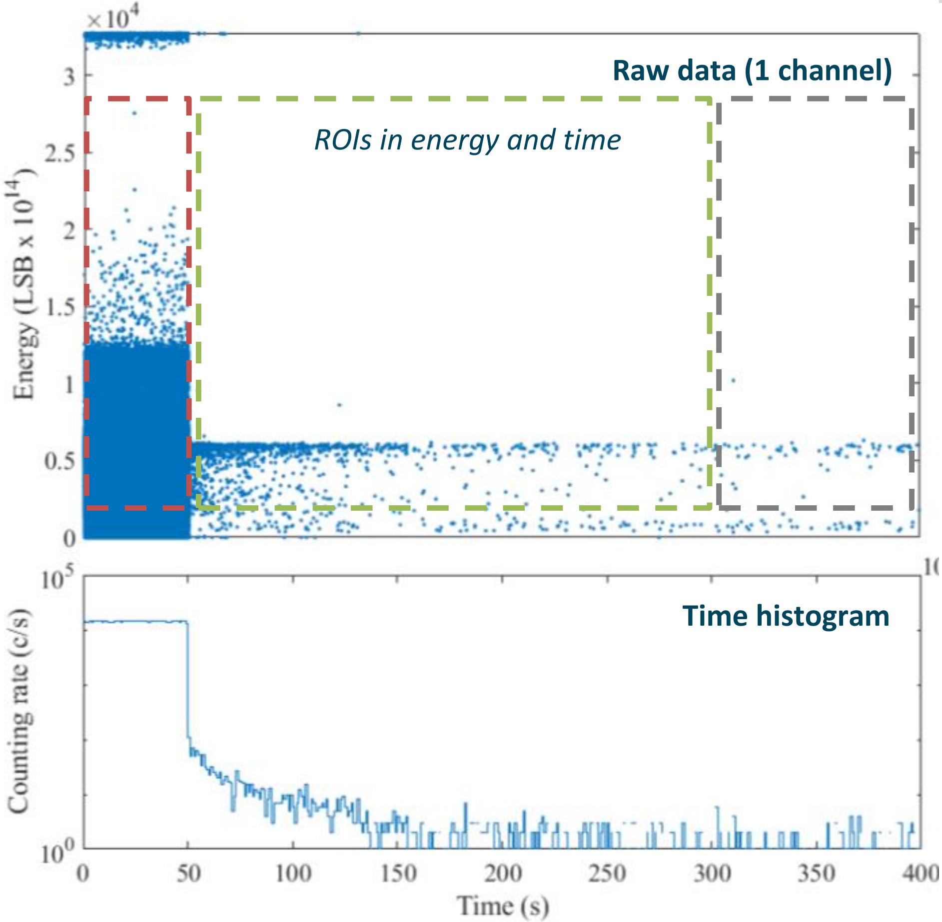
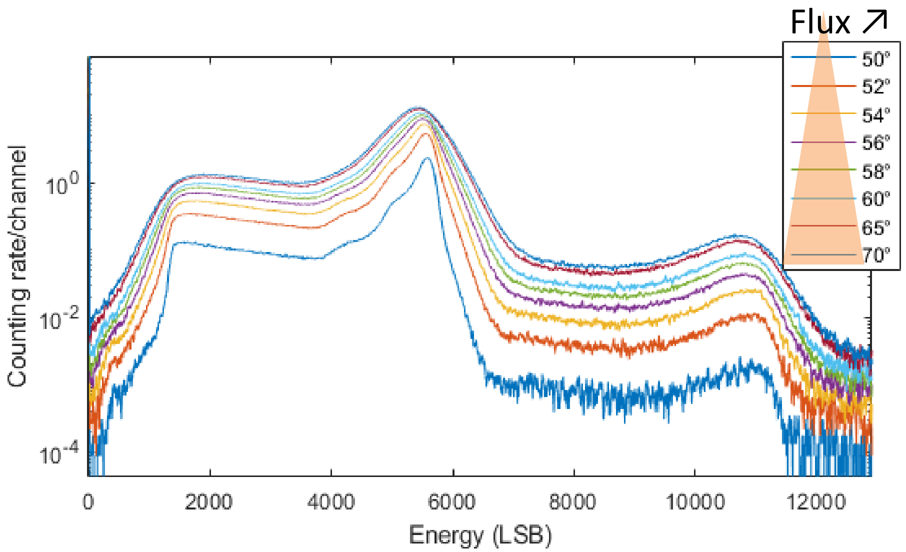
Many steps to go from list files to DN emission

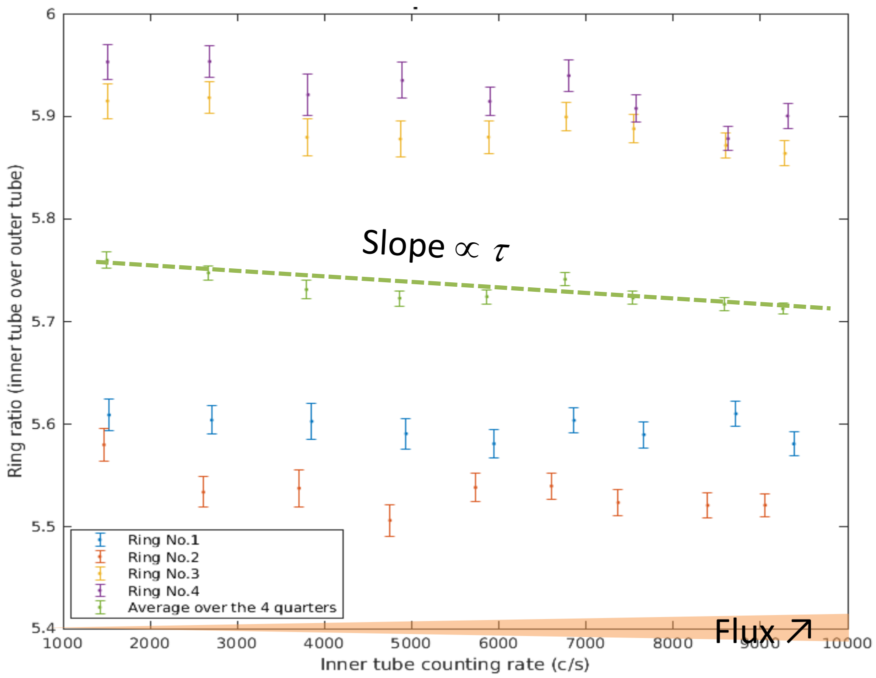
- Convert list files and sort events
- Time synchronization
- Energy calibration (scaling)
- Cut the region of interest (ROI)
- Construct histograms in energy and time
- Dead time correction
- Sum of 16 channels
- Subtraction of detection background (*beam off)*
- Iterate over files to improve statistics

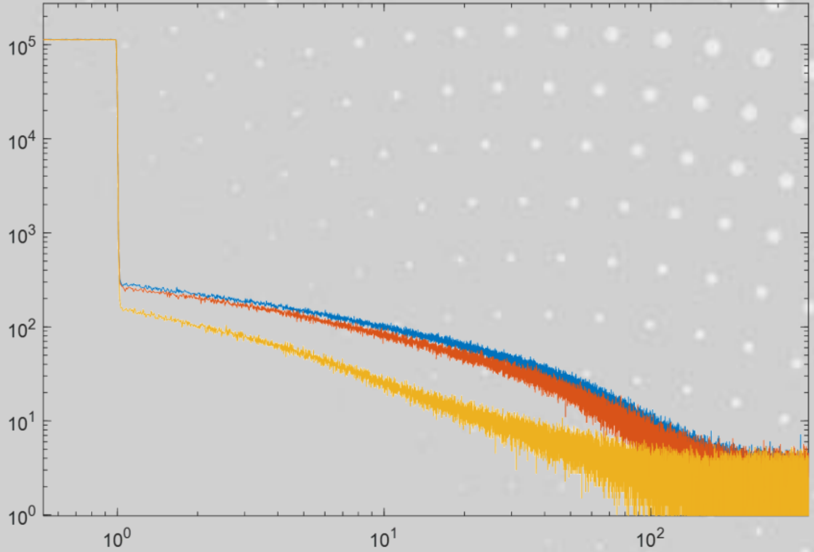




Method of the constant "ring ratio" vs. flux







4. Results & Discussion

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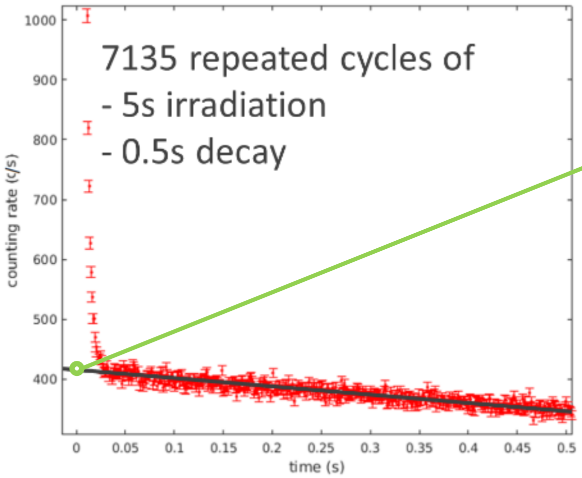
4. Results and discussion

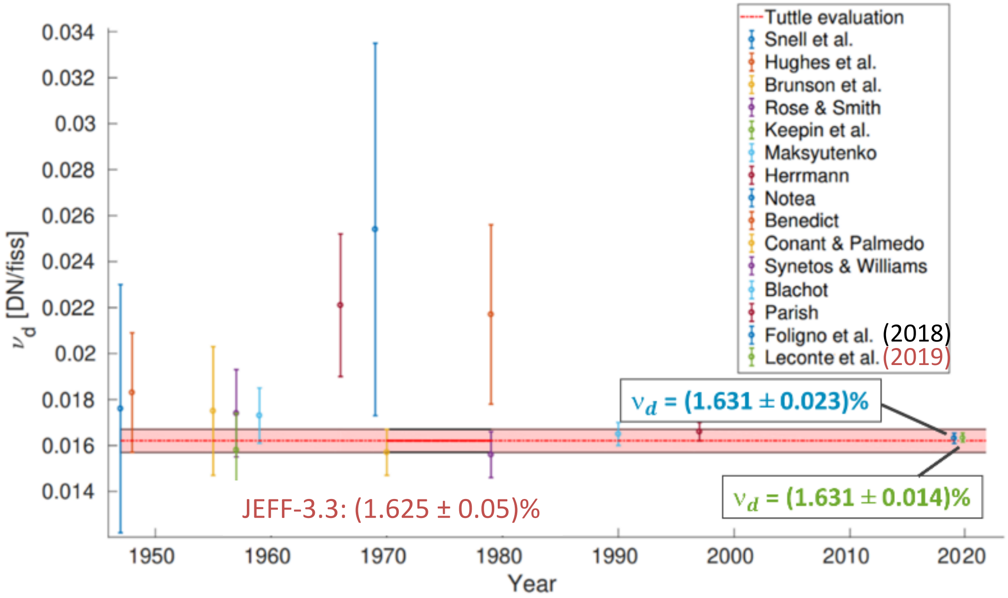
Results for ^{235}U in 2019

Delayed neutron yield (ν_d)

$$C(t) = (b_{off}) + F\nu_d\overline{\varepsilon_d}\sum_{k=1}^{8} f_k a_k \cdot \frac{(1-e^{-\lambda_k t_{irr}})\cdot e^{-\lambda_k t}}{1-e^{-\lambda_k t_m}}$$

Tends to 1 when $t_{irr} \to \infty$ & $t \to 0$





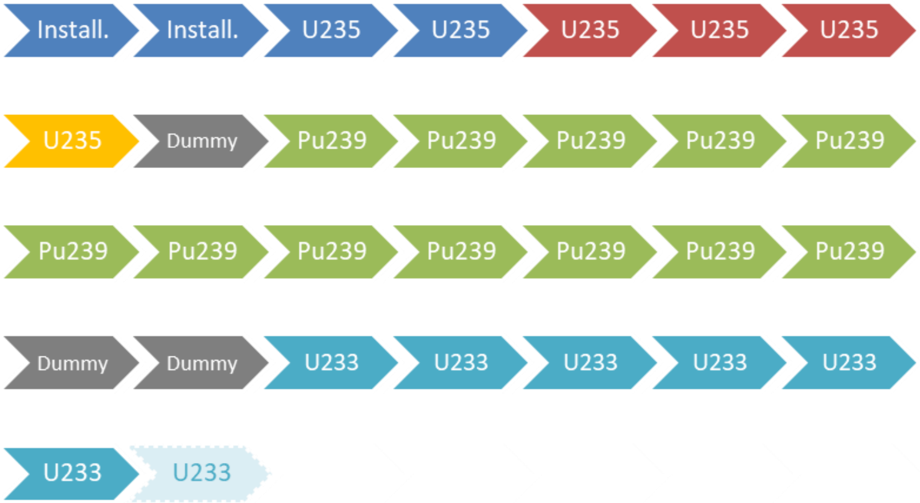
- Background count rate b_{off} negligible at $t = 0$
- Flux calibration based on prompt neutrons counting rate: $F \propto \frac{C_i}{\nu_p\,\overline{\varepsilon_p}}$

New challenges with ^{239}Pu target

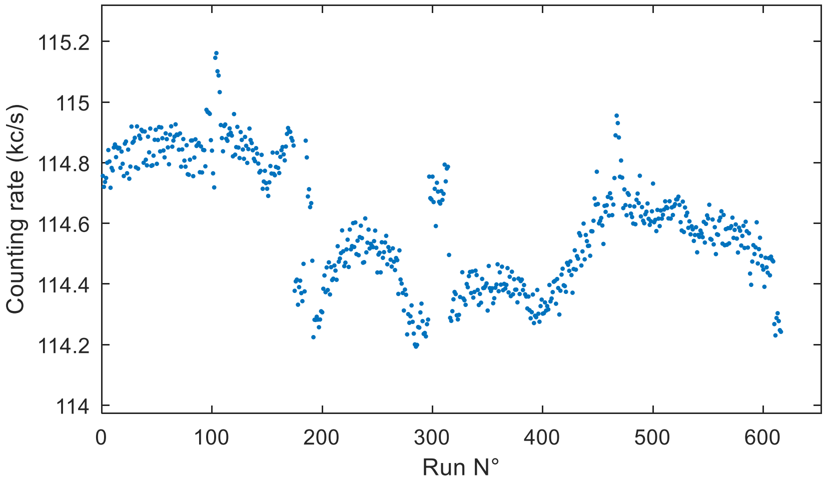
1. Safety issues to safely handle plutonium

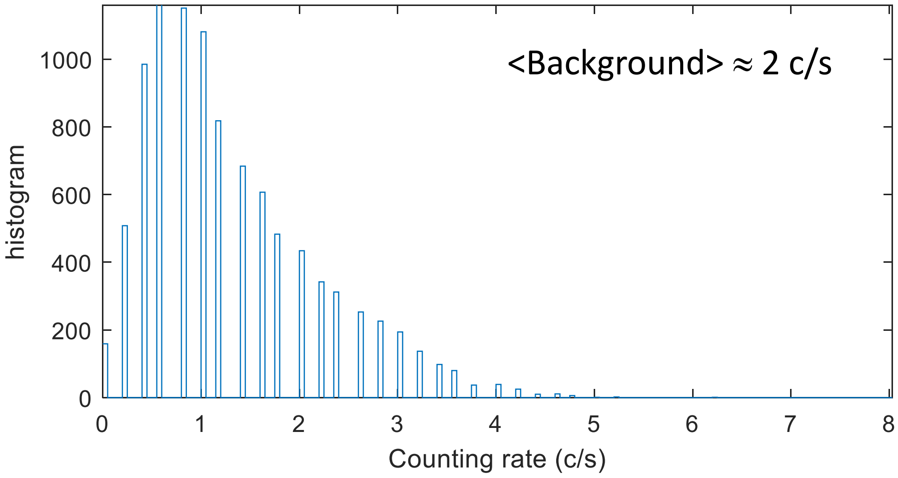
2. Much less delayed neutrons with ^{239}Pu

3. COVID restrictions to access ILL

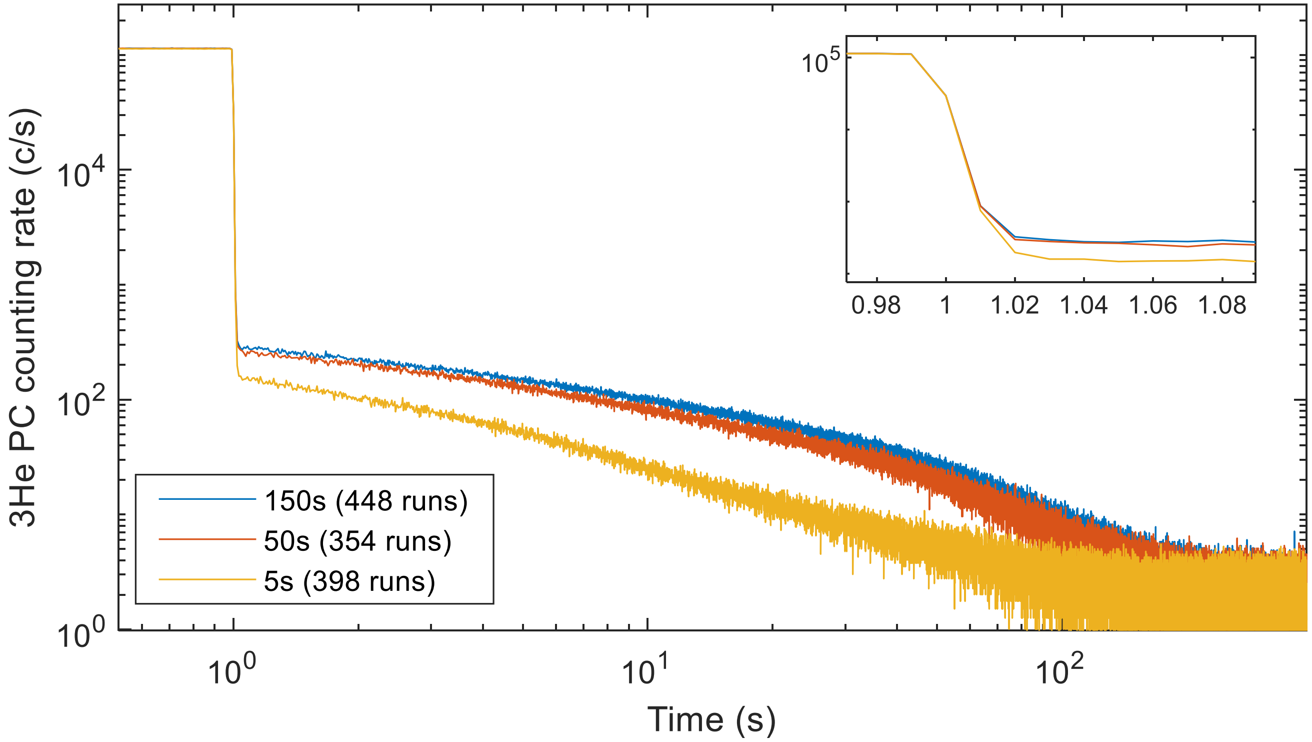


^{239}Pu over 154h: very good stability over time





DN emission of ^{239} Pu in 3 scenarios



5. Summary & Outlooks

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5. Summary and Outlooks

ALDEN is now a mature collaboration for measuring DN nuclear data

- The experimental setup is now mature and will be used to study more fissile isotopes in the future
- The recent experimental campaign focused on ^{239}Pu and ^{233}U produced satisfactory results. Data analysis is ongoing work

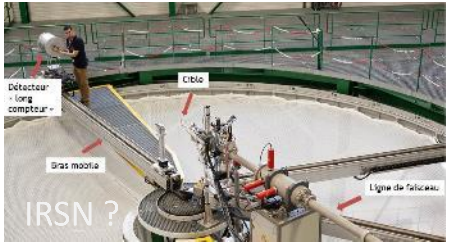
Future work

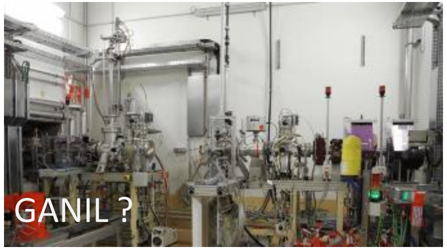
1. Thermal fission of ^{241}Pu

- Same experimental setup @ILL
- Some difficulties with target manufacturing
- Irradiation foreseen for 2023

2. Fast fission of ^{238}U

- New facility and setup to be adapted
- A PhD work will begin on the subject of improving DN of ^{238}U
- First tests of the new setup in 2023





Thank you for your attention

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ACKNOWLEDGEMENT

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