

# Absolute measurements of 14 MeV neutrons with diamond detectors

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# Fusion power assessment

## STANDARD METHOD

Counting neutrons with fission chambers cross-calibrated with activation foils

### Challenges

- Requires complex Monte-Carlo simulations
- In-vessel calibrations to validate MC simulations
- Calibrations repeated whenever modifications to the machine are made
- Flat response of fission chambers

## ALTERNATIVE METHOD

Neutron spectroscopy along a well-known collimated line of sight

- No need of intensive transport simulations
- No need of new calibration factors when machine changes are made
- Demonstrated at JET with the MPR spectrometer

$$Y_n = \frac{C_n}{T \cdot A \cdot \varepsilon}$$

$C_n$ : neutron count rate

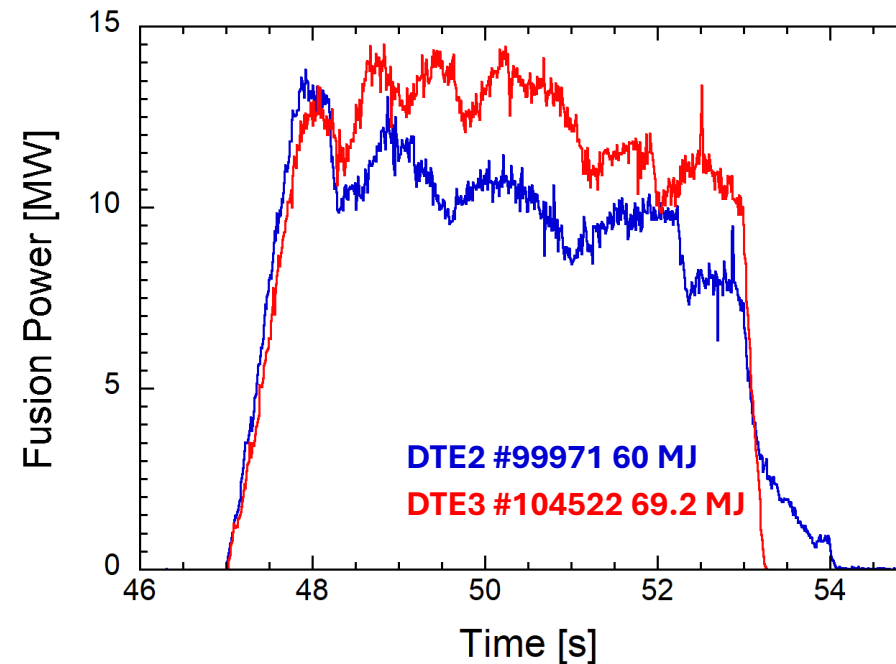
$T$ : geometric factor

$A$ : attenuation factor

$\varepsilon$ : **absolute efficiency**

# Fusion power assessment

- Neutron spectroscopy with diamond detectors
- Measurements at JET during DTE2 and DTE3 campaigns cross-calibrating with fission chambers



# Diamond detectors

## Characteristics

- High radiation hardness
- Not sensitive to magnetic field
- Room temperature operation
- Compact size
- MHz capability

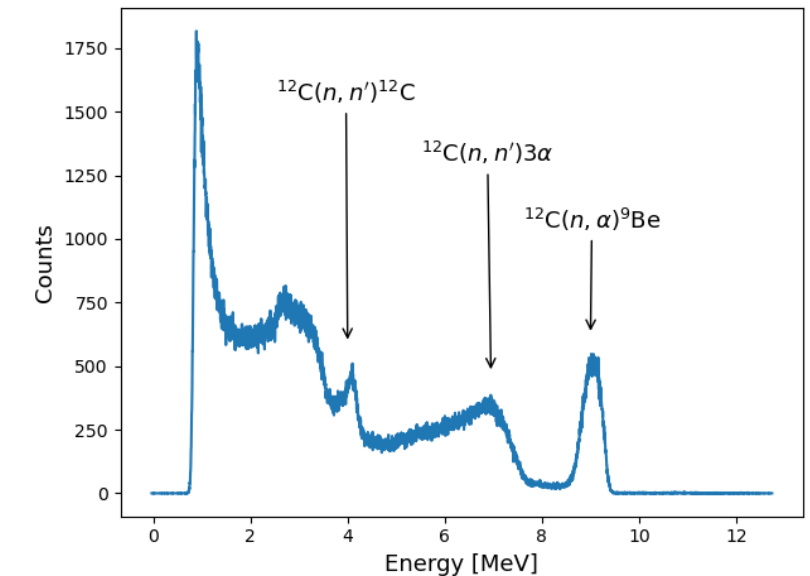
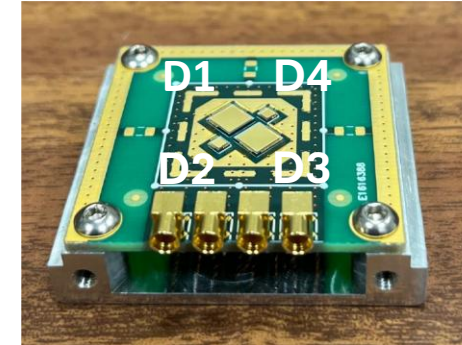
## Properties

- Spectral separation of 2.5 MeV and 14 MeV neutrons
- Spectral separation of direct and scattered neutrons

## Reaction channels

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

Only events under the n- $\alpha$  peak are considered



# Efficiency measurement at FNG

To obtain absolute measurements with a diamond detector it is necessary to know its **efficiency**

The efficiency is determined at the Frascati Neutron Generator (FNG), Italy, where the neutron yield is well known

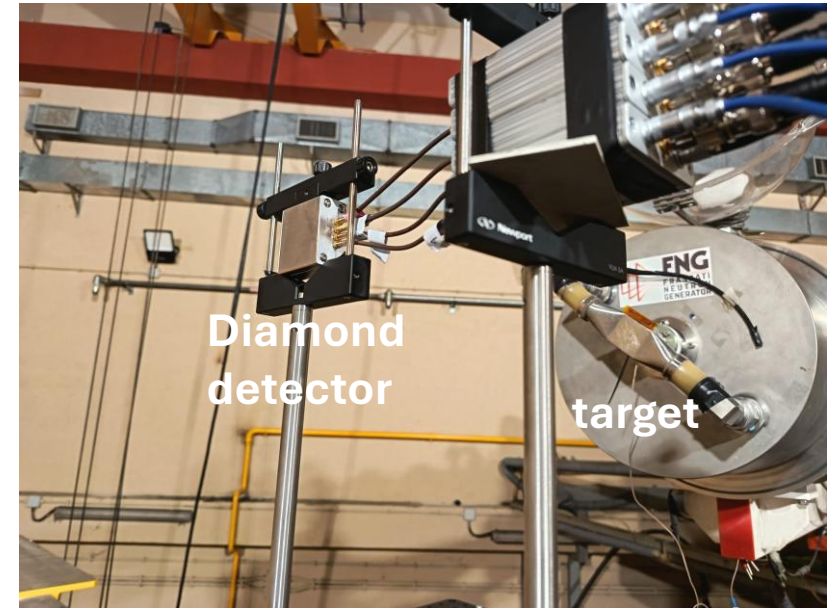
$$\varepsilon = \frac{C_{n\alpha}}{S \cdot f_d}$$

$C_{n\alpha}$ : counts under  $n\alpha$  peak

$S$ : area of the pixel

$f_d$ : fluence at the diamond position

- Area measured with a microscope
- Fluence determined with activation foils

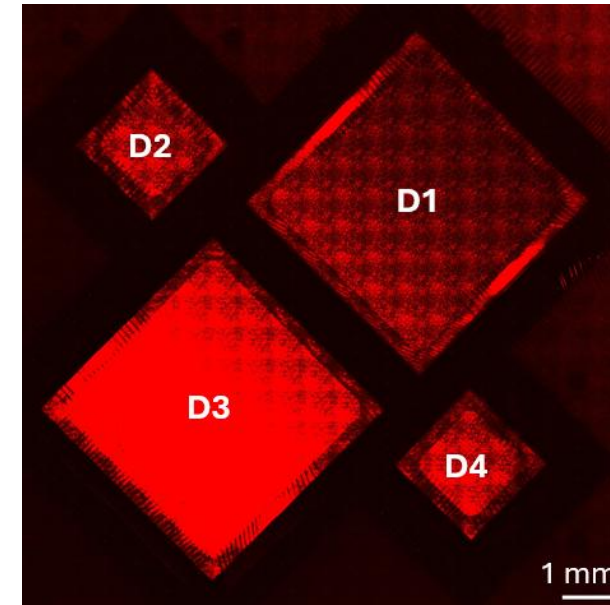


# Efficiency measurement at FNG

## ACTIVE AREA MEASUREMENTS

- Measurements with confocal fluorescence microscope operated in reflection mode and analysed with ImageJ
- Contacts smaller than diamond surface to avoid discharges → active area given by the contact surface
- No access to the bottom contact

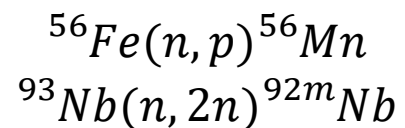
| Pixel | Diamond (cm <sup>2</sup> ) | Contact (cm <sup>2</sup> ) |
|-------|----------------------------|----------------------------|
| D1    | 0.209                      | 0.163                      |
| D2    | 0.040                      | 0.022                      |
| D3    | 0.208                      | 0.165                      |
| D4    | 0.040                      | 0.023                      |



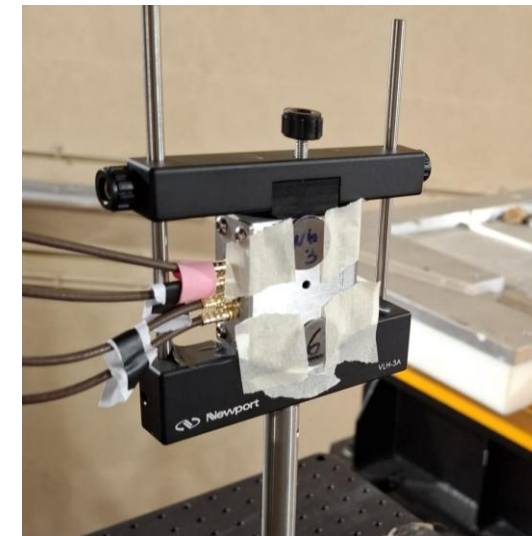
# Efficiency measurement at FNG

## FLUENCE MEASUREMENTS

- Activation foils



- Positioned in contact with the diamond detector casing
- Cross section from IRDFF-II weighted on the spectrum measured with the diamond detector
- Gamma rays measured with a HPGe detector
- Very good agreement with alpha particle method



# Efficiency measurement at FNG

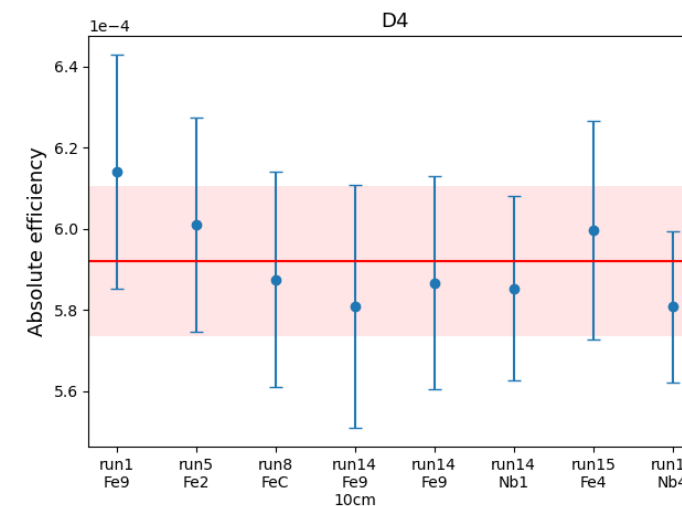
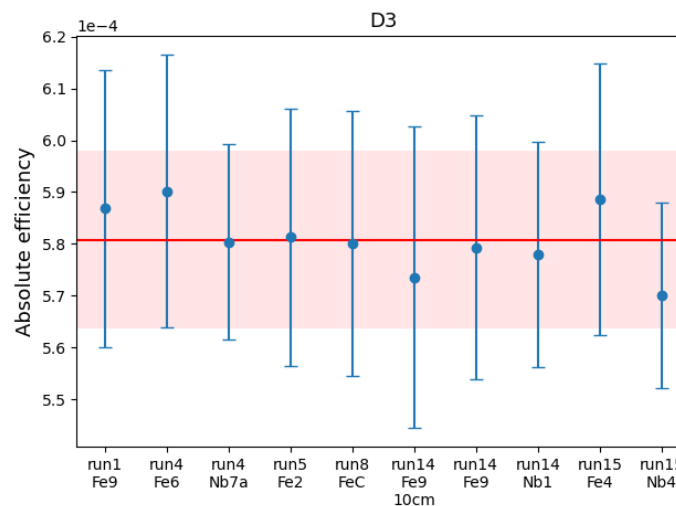
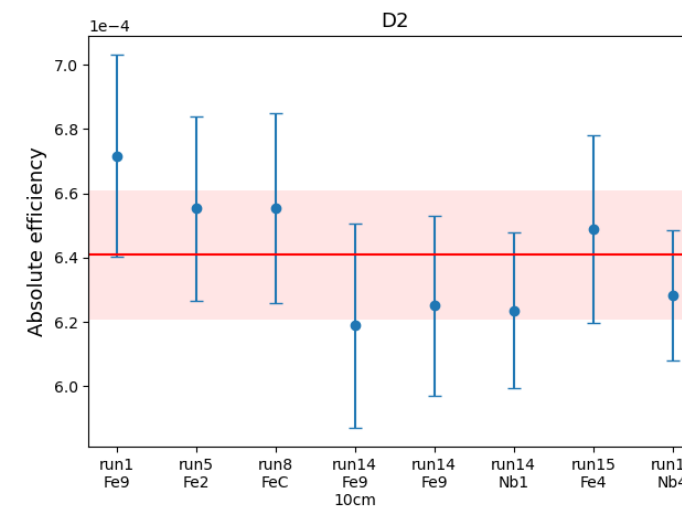
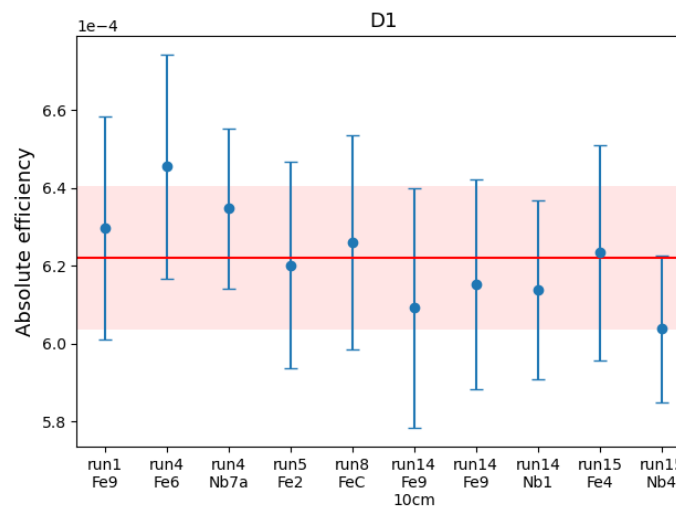
Mean efficiency

$$\varepsilon_{D1} = (6.22 \pm 0.18) \text{E-04}$$

$$\varepsilon_{D2} = (6.41 \pm 0.20) \text{E-04}$$

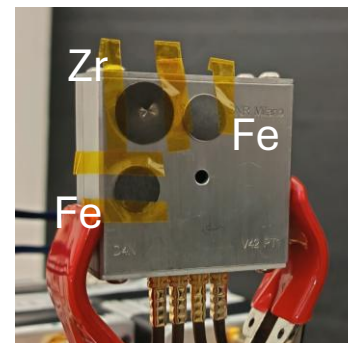
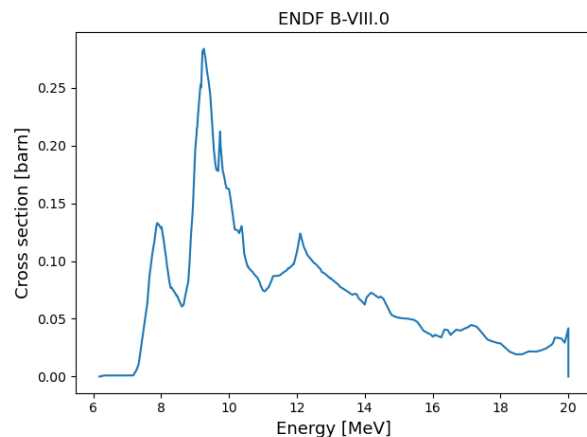
$$\varepsilon_{D3} = (5.81 \pm 0.17) \text{E-04}$$

$$\varepsilon_{D4} = (5.92 \pm 0.18) \text{E-04}$$

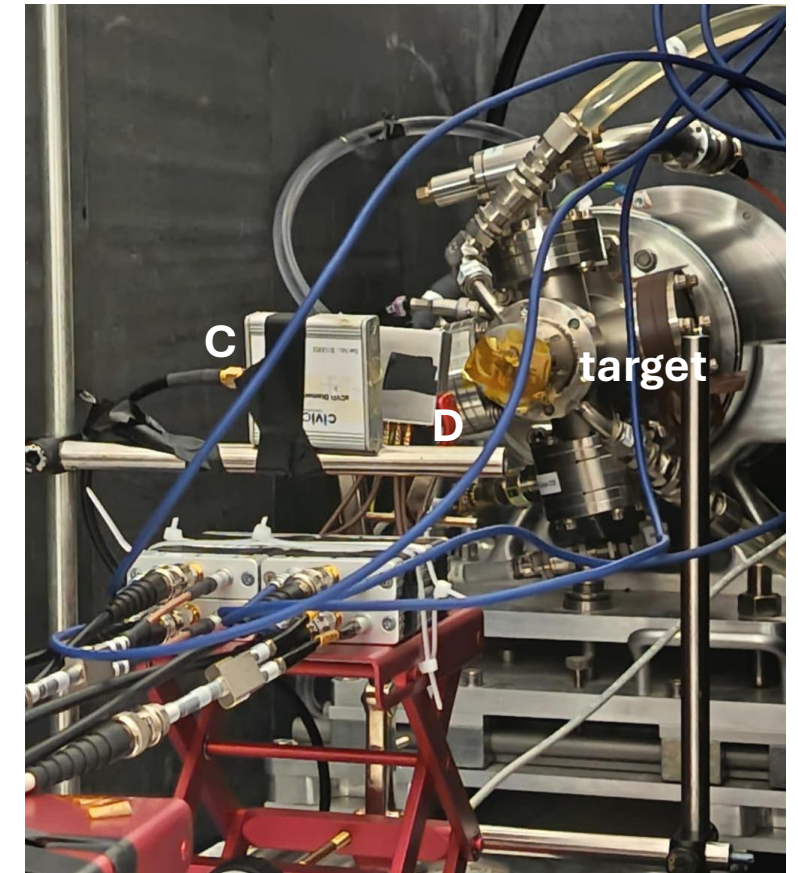


# Benchmark at NILE

- The efficiency obtained at FNG is verified at the Neutron Irradiation Laboratory for Electronics (NILE), UK, by measuring the neutron yield of the source
- Measurements are taken simultaneously with a metrology calibrated diamond detector C and activation foils to validate the results
- MCNP simulations are performed to estimate the attenuation of 14MeV neutrons through the interfering materials
- Different energy from FNG → correction for n- $\alpha$  cross-section

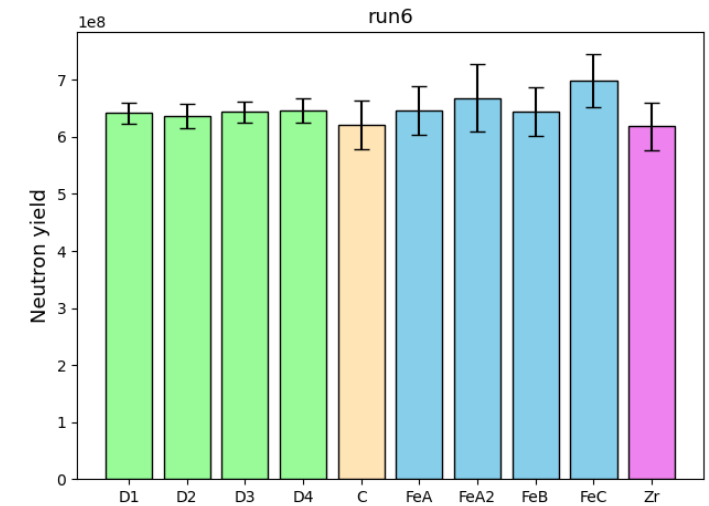
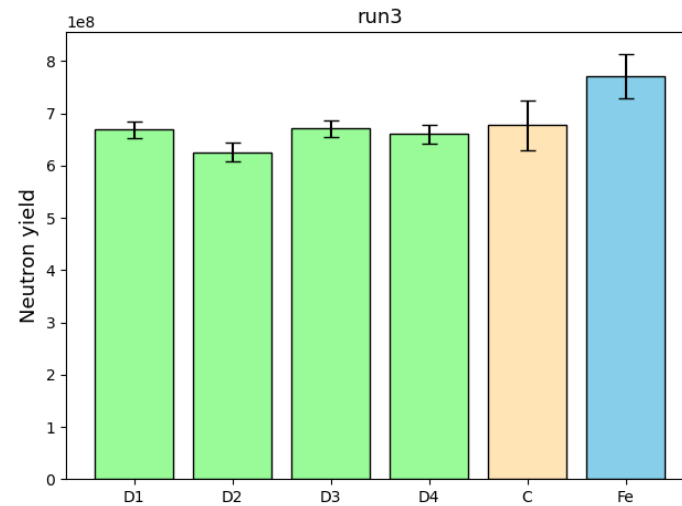
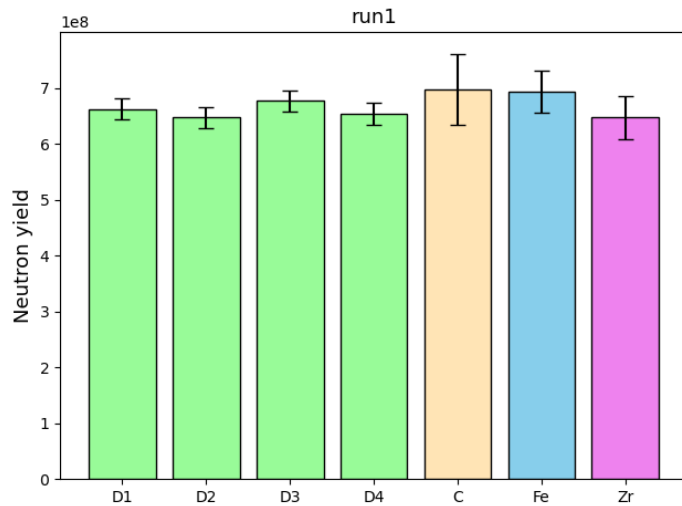


*Diamond matrix with activation foils*



*Experimental set-up at the NILE facility*

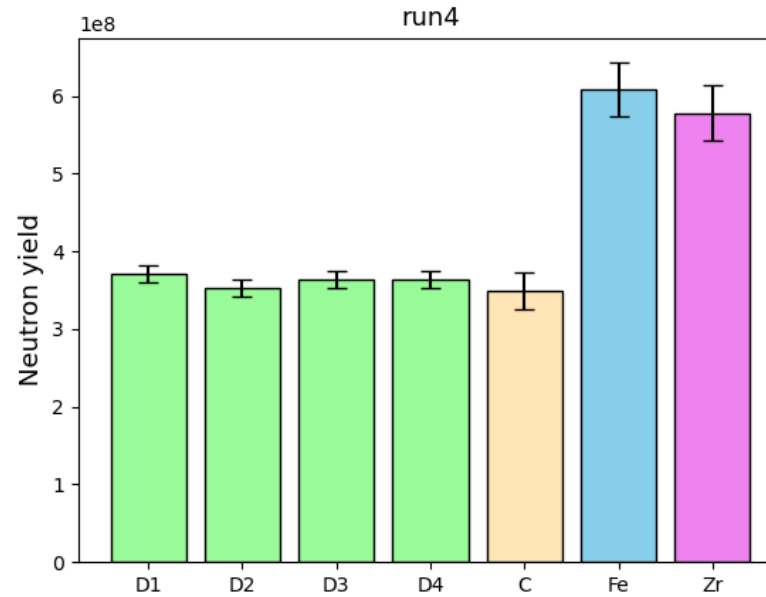
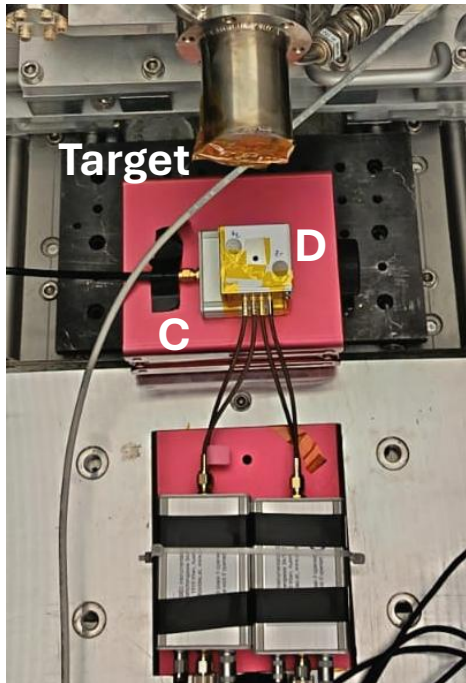
## MEASUREMENTS AT 0°



- Diamond matrix pixels
- Metrology calibrated diamond detector
- Fe activation foil
- Zr activation foil

- Very good agreement!
- Uncertainty on the neutron yield with the diamond matrix within 3%

## MEASUREMENTS AT 90°



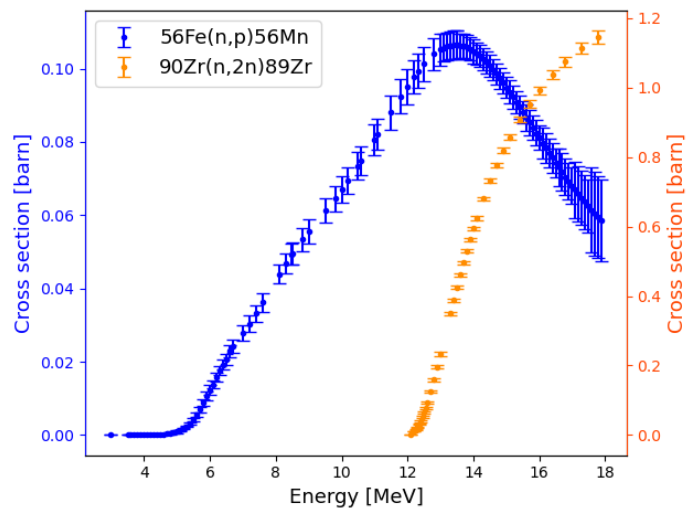
- 40% difference between diamonds and activation foils
- Activation foils detect more neutrons than diamonds

# 1<sup>st</sup> hypothesis → scattered neutrons

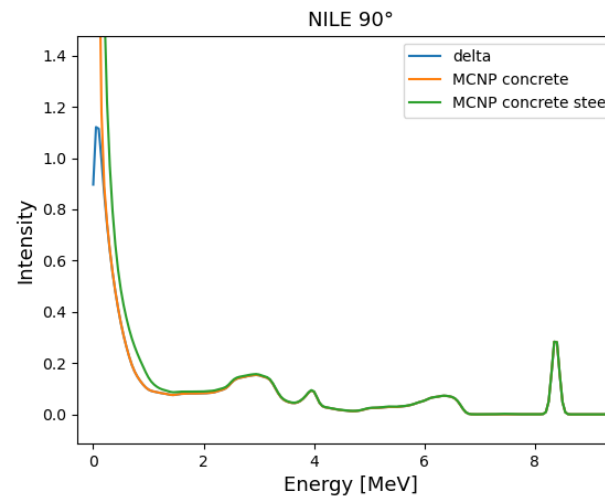
## Problems

1. Threshold of Zr activation >12 MeV
2. MCNP simulations: scattered neutrons on concrete have too low energy
3. Comparison between 0° and 90° for activation foils and diamond

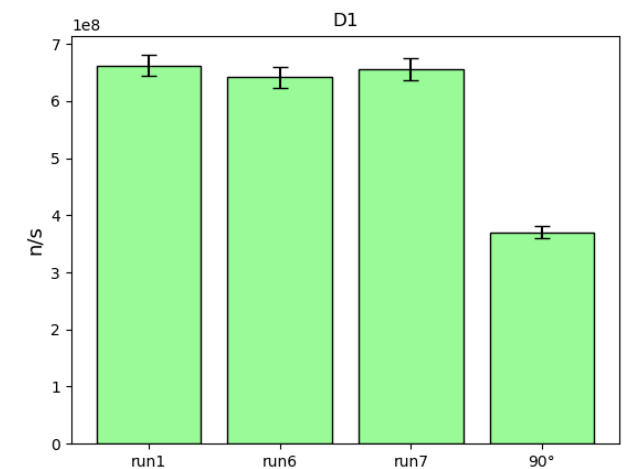
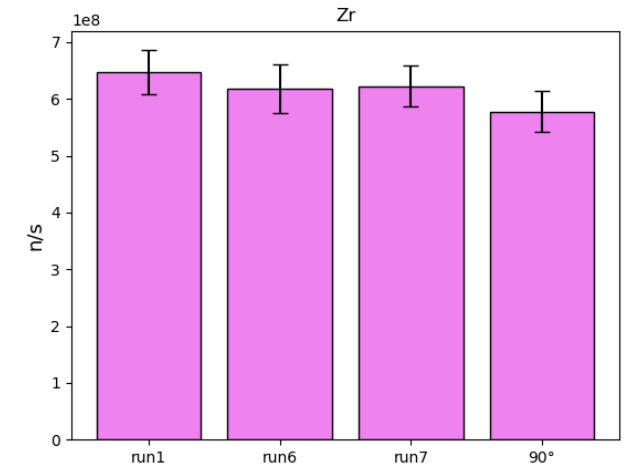
1.



2.

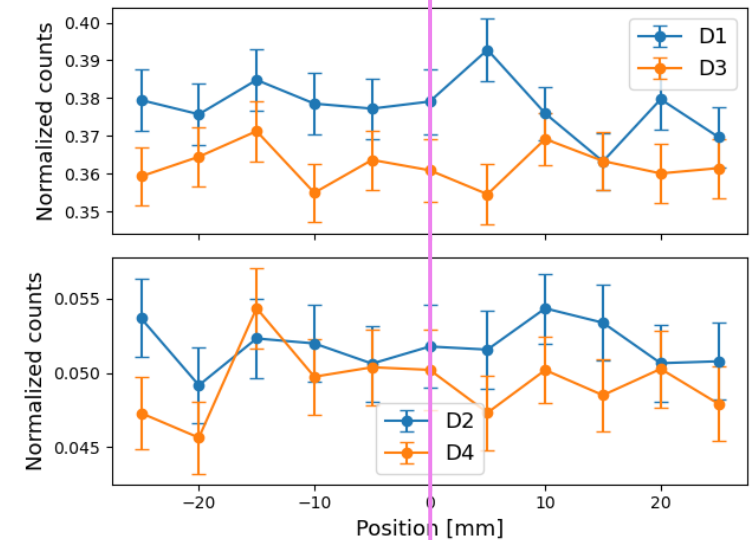
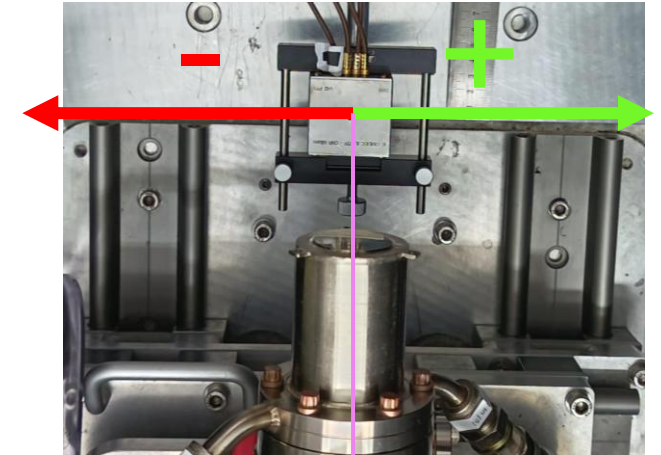
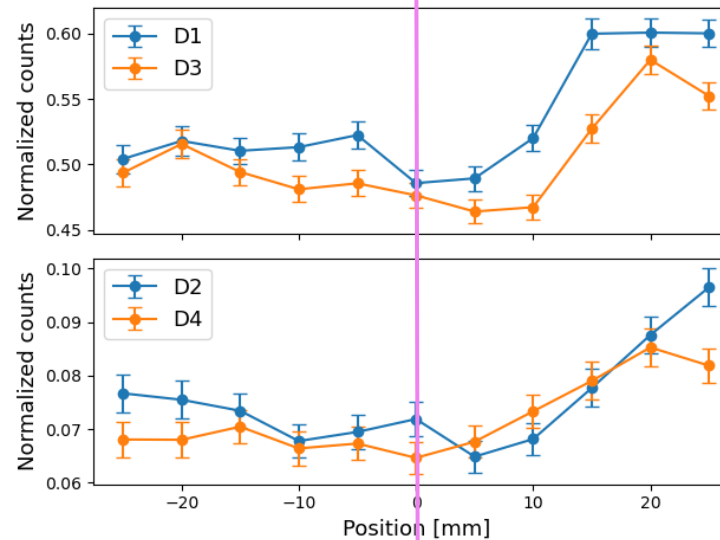
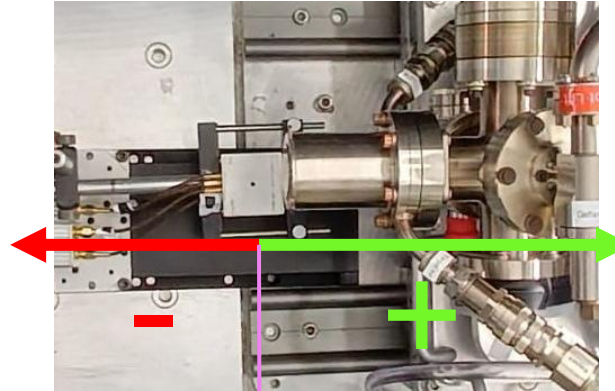


3.



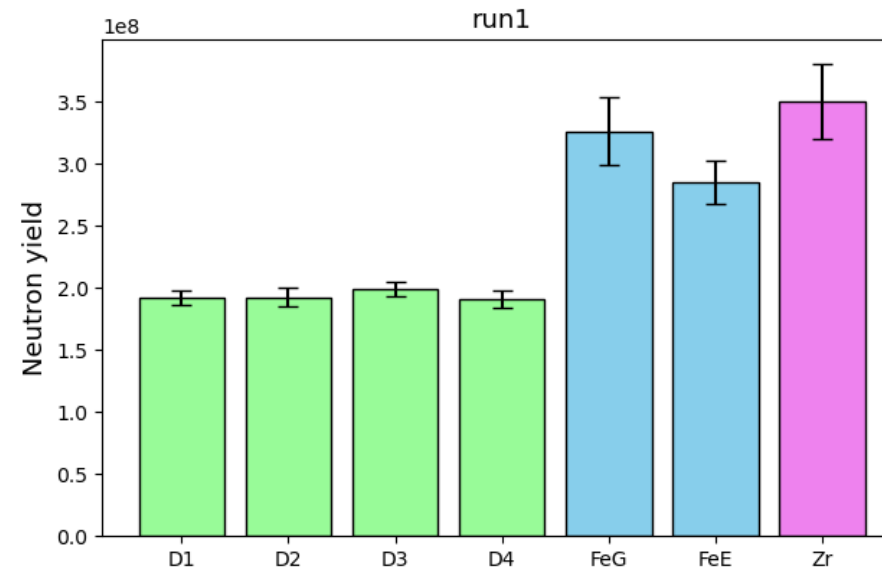
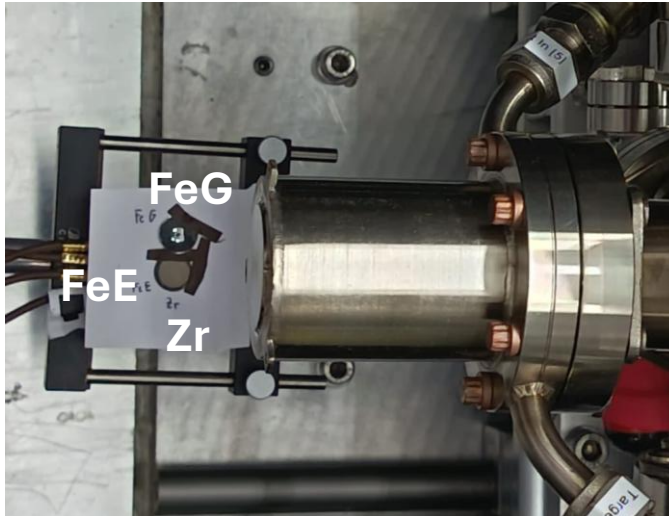
## 2<sup>nd</sup> hypothesis → materials around target

- Depression of intensity due to materials around target  
→ Diamond exactly under the material, activation foils just after
- Diamond counts normalized to fission chamber
- Change in neutron flux in 2 cm

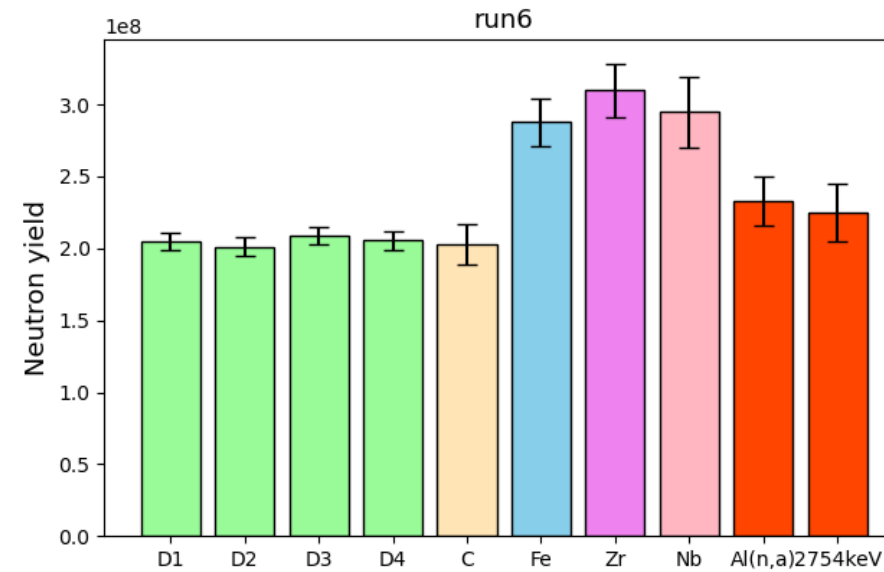
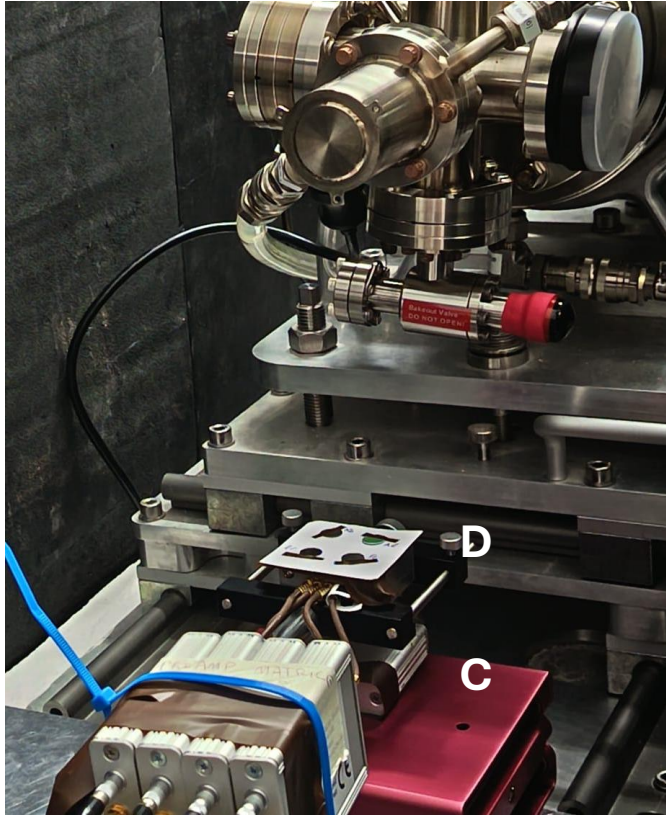


## 2<sup>nd</sup> hypothesis → materials around target

- To validate the hypothesis → measurements at 90° with 3 activation foils, 2 of which in the centre of the matrix
- If the hypothesis is true, FeE and Zr should measure the same neutron yield as the diamond

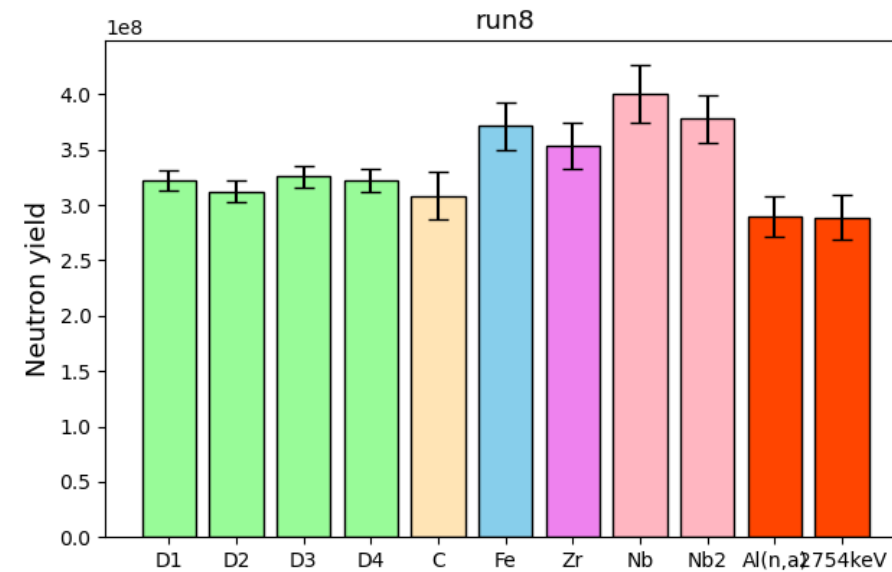
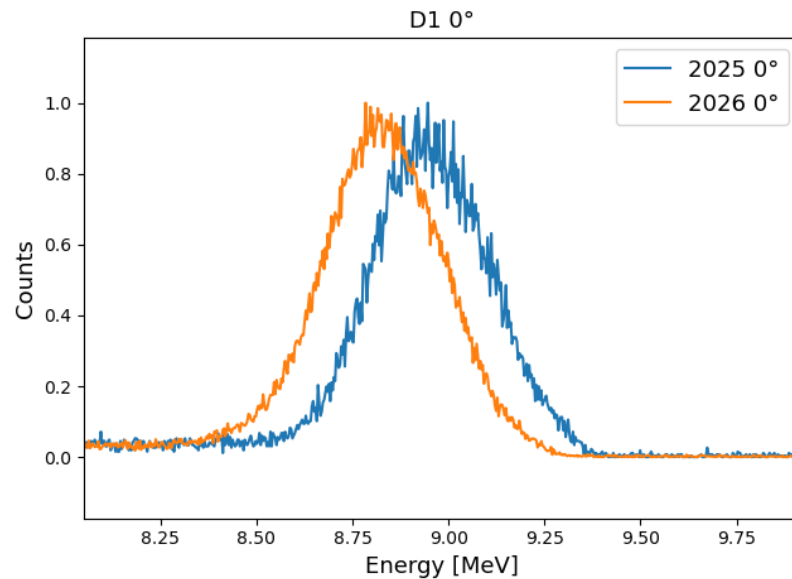


- The diamond is now placed at 90° moved by 2cm from the target

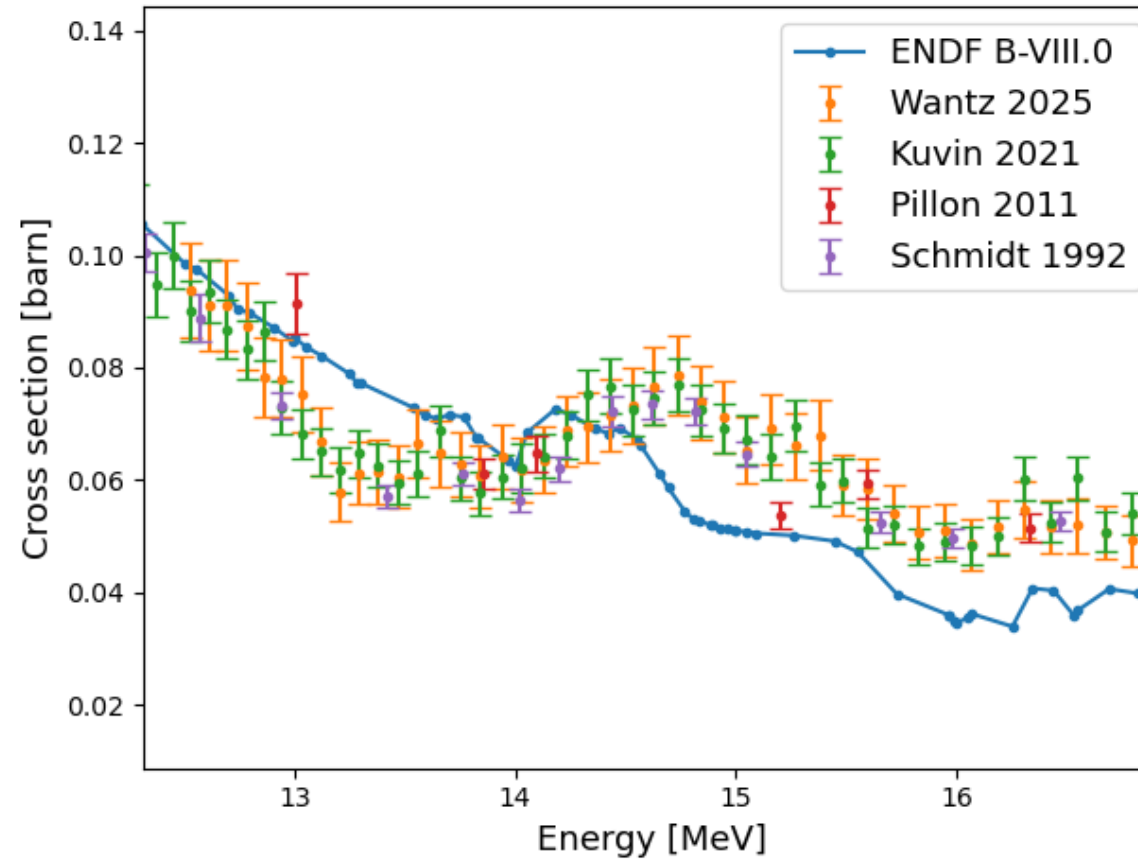


## MEASUREMENT AT 0°

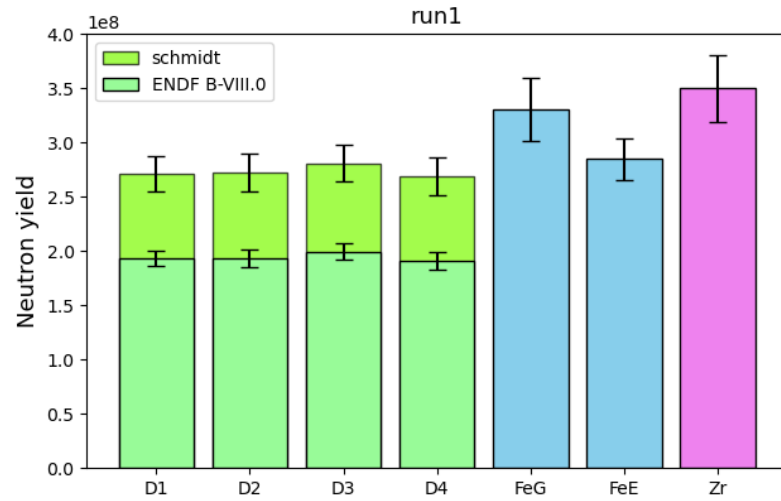
- To verify stability over time
- The voltage in 2026 is 105kV, in 2025 it was 120kV → The energy at 0° in 2026 is lower than the one in 2025



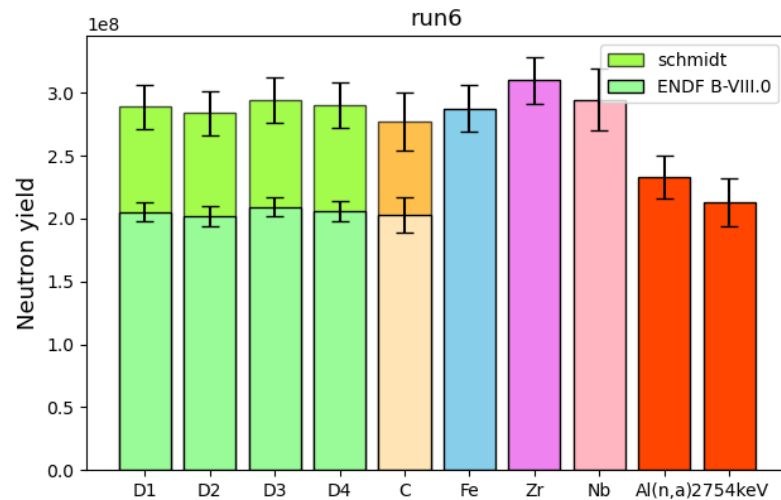
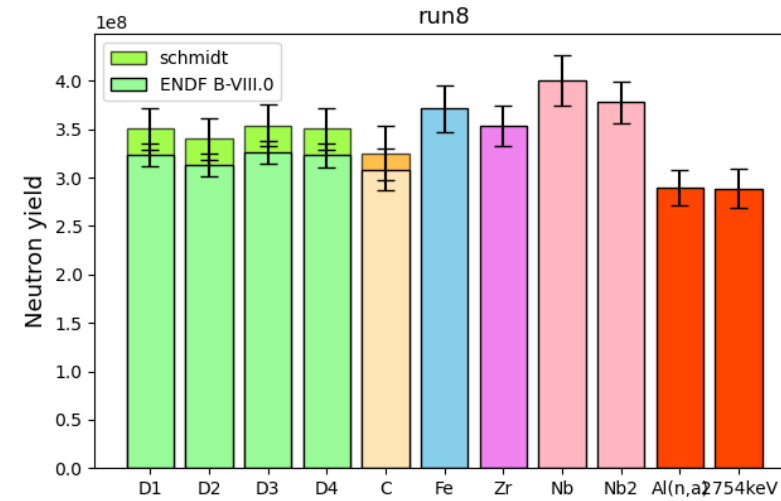
3<sup>rd</sup> hypothesis → n-α cross section not well known



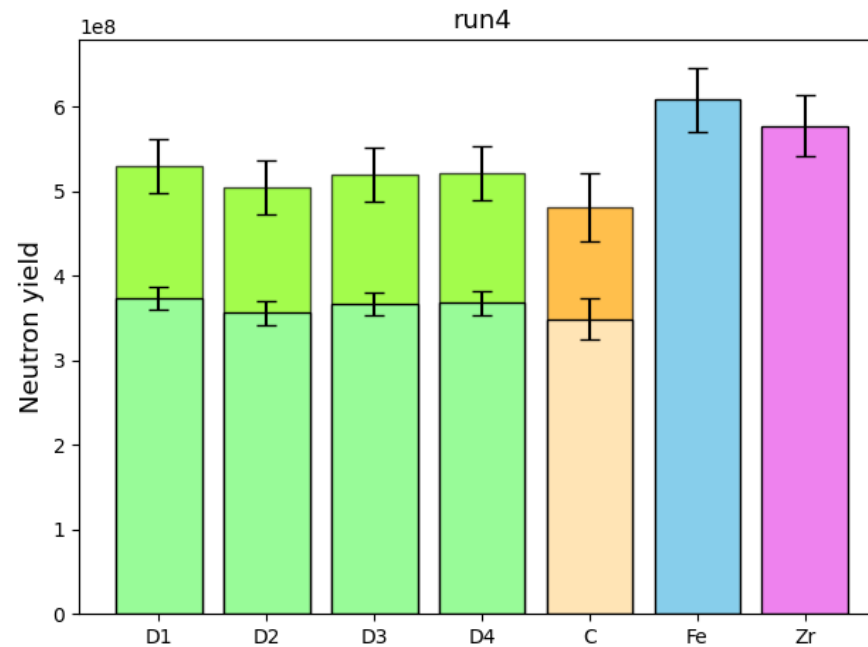
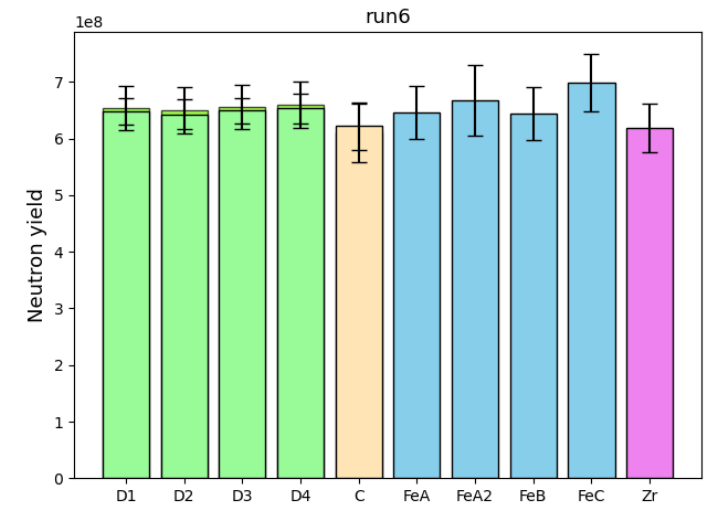
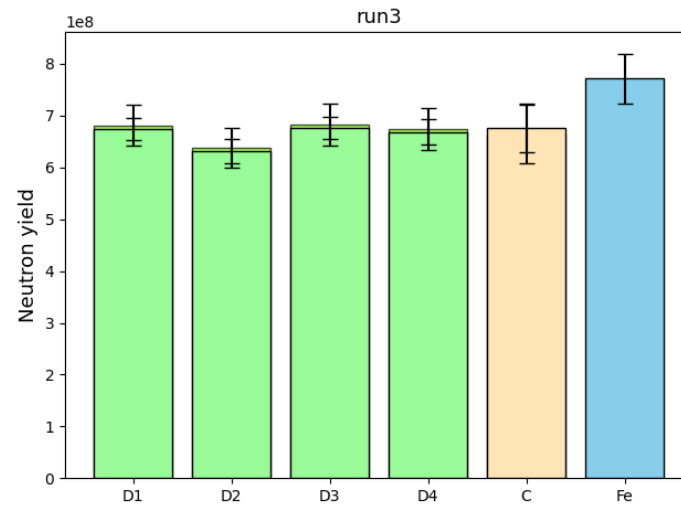
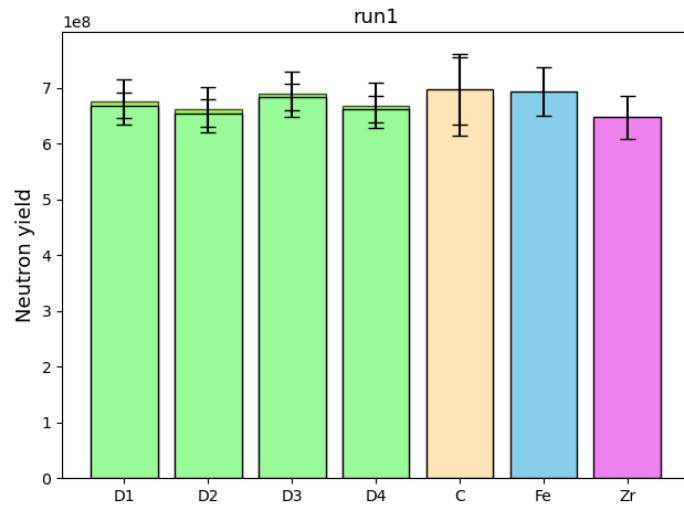
90°



0°



- Better agreement!
- Still discrepancy when exactly under the target (run1)
- Uncertainty on the neutron yield within 6%



- Very high improvement at 90° but still discrepancy

## Theoretic efficiency

$$\varepsilon_{theoric} = \frac{\rho \cdot N_a \cdot \sigma \cdot z}{M}$$

| Cross-section | Efficiency |
|---------------|------------|
| ENDF B-VIII.0 | 5.2E-4     |
| Schmidt       | 6.24E-4    |

## Experimental efficiency

$$\varepsilon_{D1} = (6.22 \pm 0.18)E-04$$

$$\varepsilon_{D2} = (6.41 \pm 0.20)E-04$$

$$\varepsilon_{D3} = (5.81 \pm 0.17)E-04$$

$$\varepsilon_{D4} = (5.92 \pm 0.18)E-04$$

| Pixel | Thickness ( $\mu\text{m}$ ) |
|-------|-----------------------------|
| D1    | 498 $\pm$ 22                |
| D2    | 513 $\pm$ 24                |
| D3    | 465 $\pm$ 21                |
| D4    | 474 $\pm$ 22                |

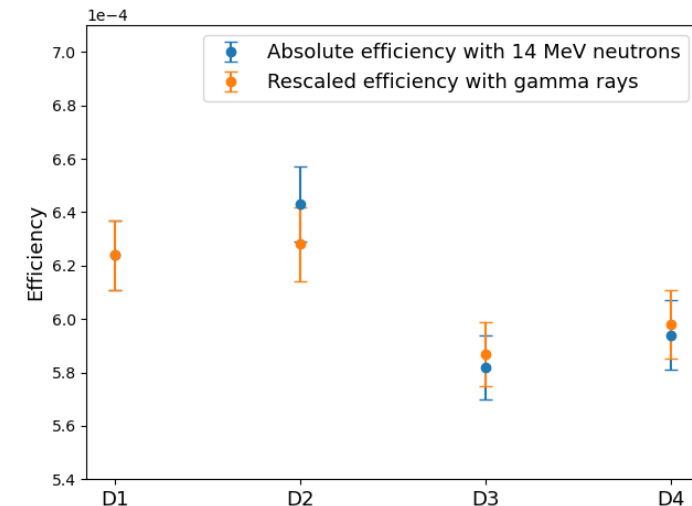
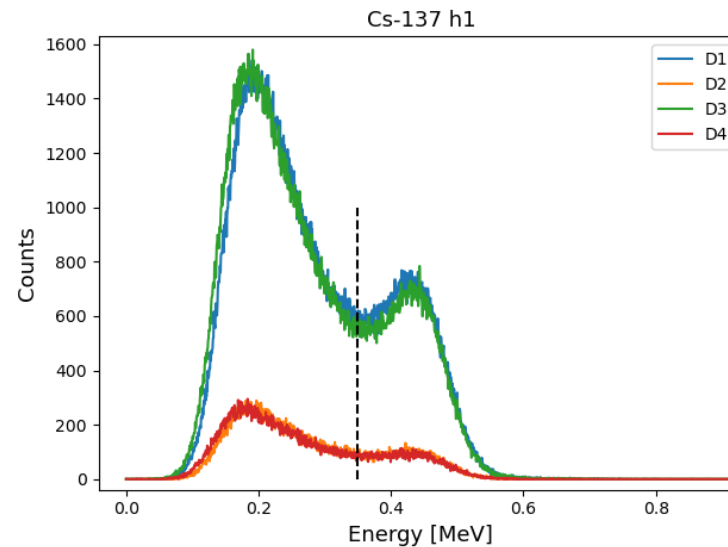
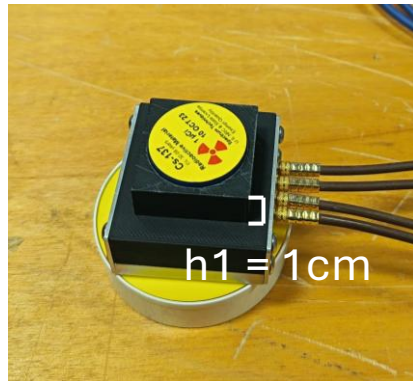
Considering experimental cross-section (Schmidt)

# Is it necessary to absolute calibrate every single pixel with neutrons?\*

- Suppose pixel D1 is correctly absolutely calibrated
- Is it possible to determine the efficiency of the other pixels from gamma-ray measurements?

$$\varepsilon = \frac{C_{n\alpha}}{S \cdot f_d} \longrightarrow \varepsilon_{Di} = \varepsilon_{D1} \frac{S_1}{C_{\gamma 1}} \frac{C_{\gamma i}}{S_i}$$

$C_{\gamma i}$ : counts of the Compton edge for pixel  $i$   
 $S_i$ : surface of the pixel  $i$



\*Preliminary results

# Conclusions

- The efficiency of the diamond detector has been evaluated at FNG and validated at the NILE facility
- The neutron yield at NILE has been evaluated with the diamond matrix with uncertainty within 6%
- The ENDF cross-section is not suitable for these measurements → Schmidt cross-section is chosen
- Measurements with gamma-rays allowed to determine the efficiency of the pixels considering D1 as absolutely calibrated → efficiency measurement reduced to microscope measurements
- Understand Al-27 activation foils behaviour
- Validate the method at the National Physical Laboratory → end of 2026
- Calibrate diamond detectors installed at JET
- Determine the efficiency of a diamond detector ab-initio

## Periods abroad

- From 29/06/2026 to 11/07/2026 in Rutherford Appleton Laboratory, UK.

## Acquired CFU

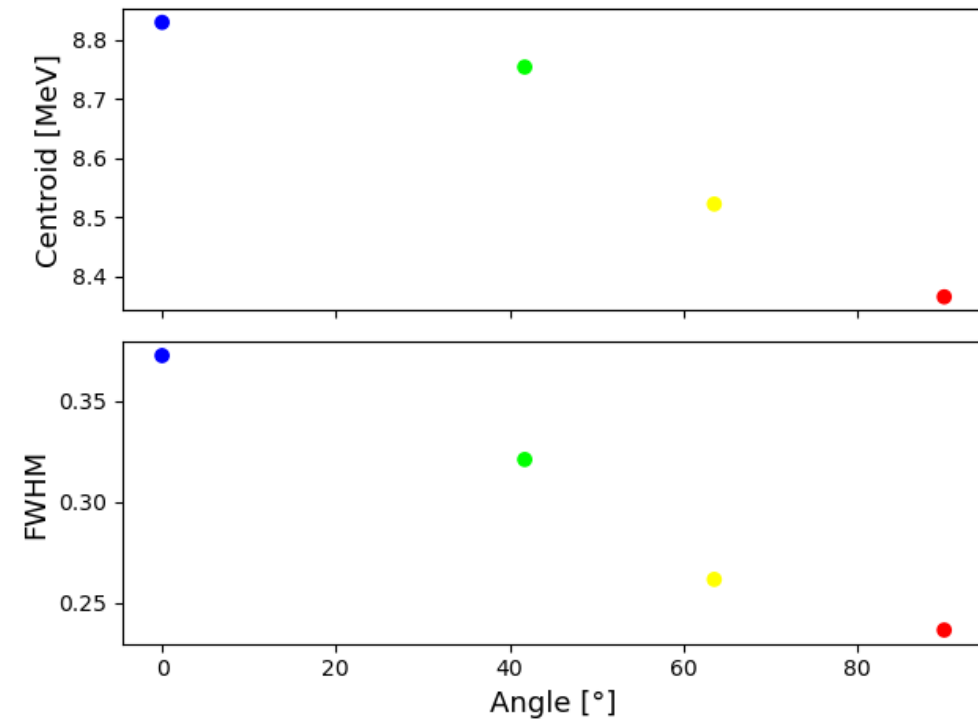
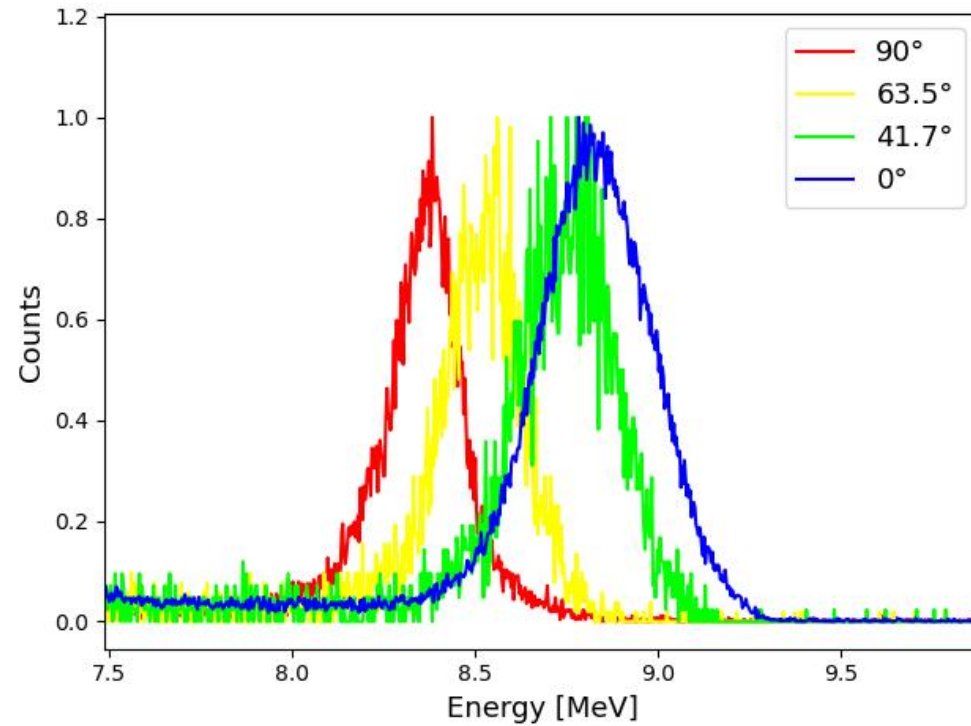
- Recent developments in experimental physics - 1 CFU
- Cold atmospheric plasma application in life sciences - 1 CFU

## Conferences

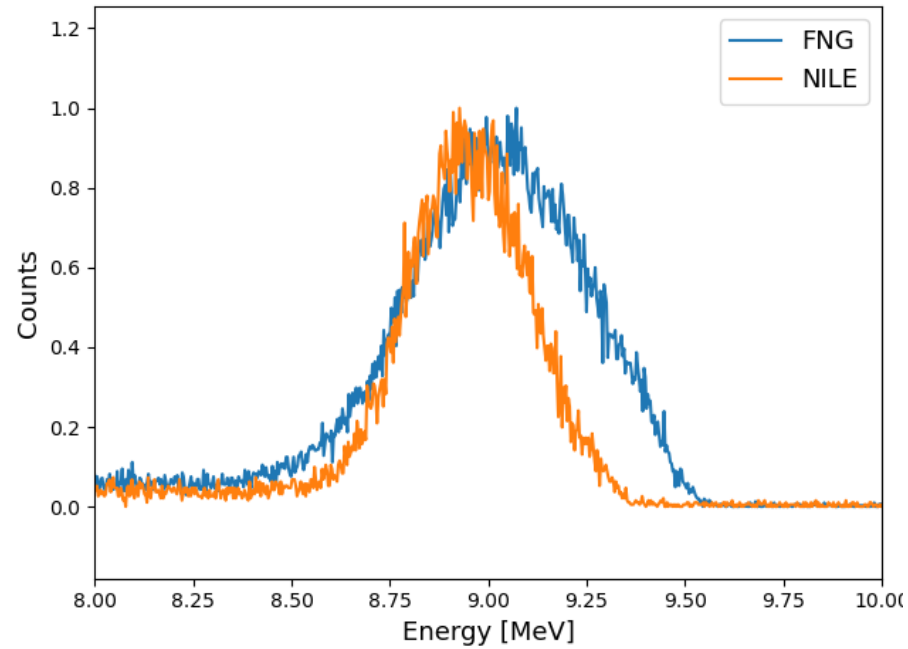
- Conferenza Italiana Plasmi (CIP), February 3-6 2026, ENEA Centro Ricerche Frascati, Italy - Poster.
- High Temperature Plasma Diagnostics (HTPD 2026), June 7-11 2026, MIT Plasma Science & Fusion Center, Boston, Massachusetts, United States - Poster.
- DT-LAB 2026 workshop, July 1-2 2026, Rutherford Appleton Laboratory, UK - Oral.

# Thank you

## Scan along angles



# FNG and NILE spectra



# Errors evaluation

## Efficiency

- Distance foil-target
- Distance diamond-target
- Diamond counts
- HPGe counts
- HPGe efficiency
- Times
- Neutron activation cross sections

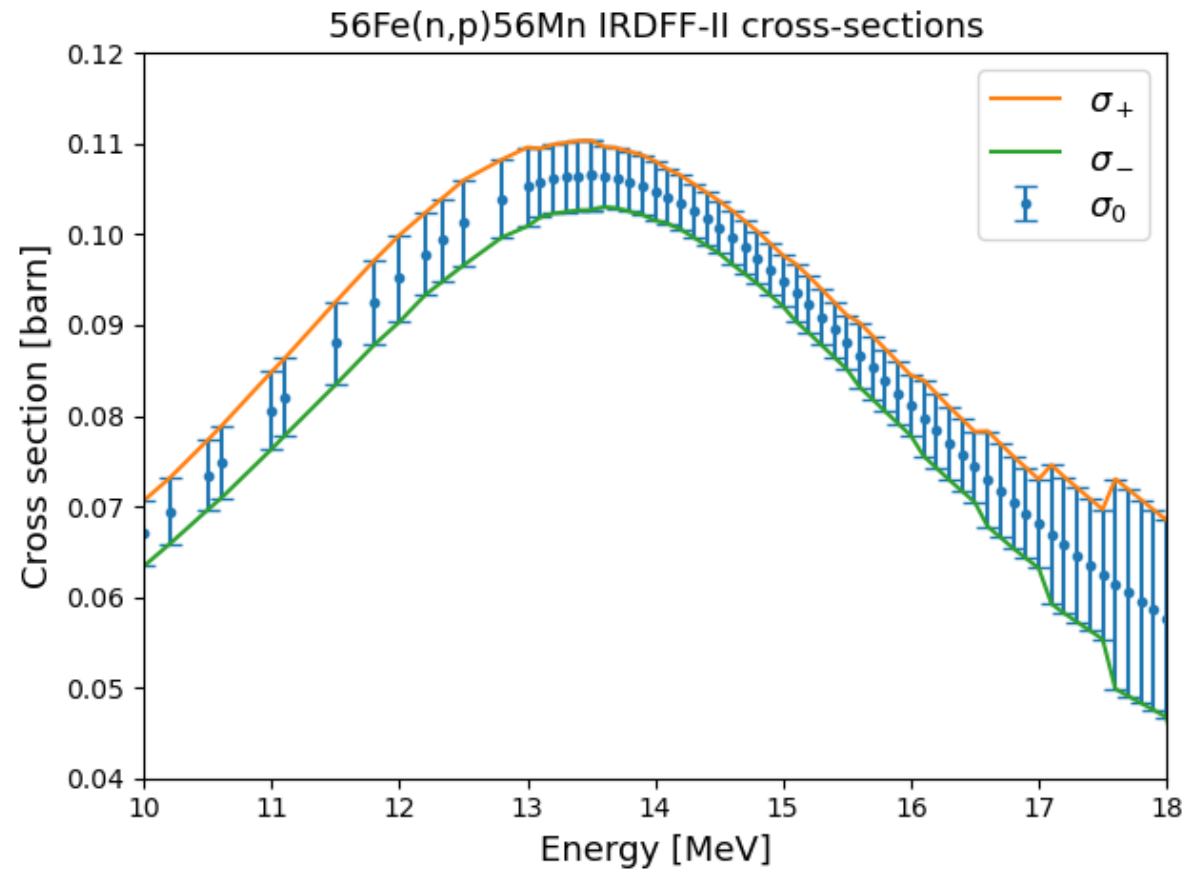
## Neutron yield with diamond

- Distance diamond-target
- Diamond counts
- Diamond efficiency
- Times
- MCNP attenuation
- $n\alpha$  cross section

## Neutron yield with activation foils

- Distance foil-target
- HPGe counts
- HPGe efficiency
- Times
- MCNP attenuation
- Neutron activation cross sections

# Cross-section uncertainty



# HPGe efficiency

- HPGe efficiency is estimated with MCNP considering the exact dimensions of activation foils
- To evaluate the error of this efficiency, the measured efficiency with different point sources is compared with point sources simulations
- At high energies there is good agreement. At low energies, the dimension of the dead layer is very important → the right thickness must be used
- Study on the centring of the source

