Study of semiconductor detectors' performance at NEAR

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J. Bartolomé[4], Z. Eleme[5], V. Foteinou[5], C. Guerrero[4], D. Hainz[2], E. Jericha[2],
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and the n_TOF Collaboration[6]

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[2]TU Wien, Atominstitut, Stadionallee 2, 1020 Wien, Austria

[3]www.cividec.at

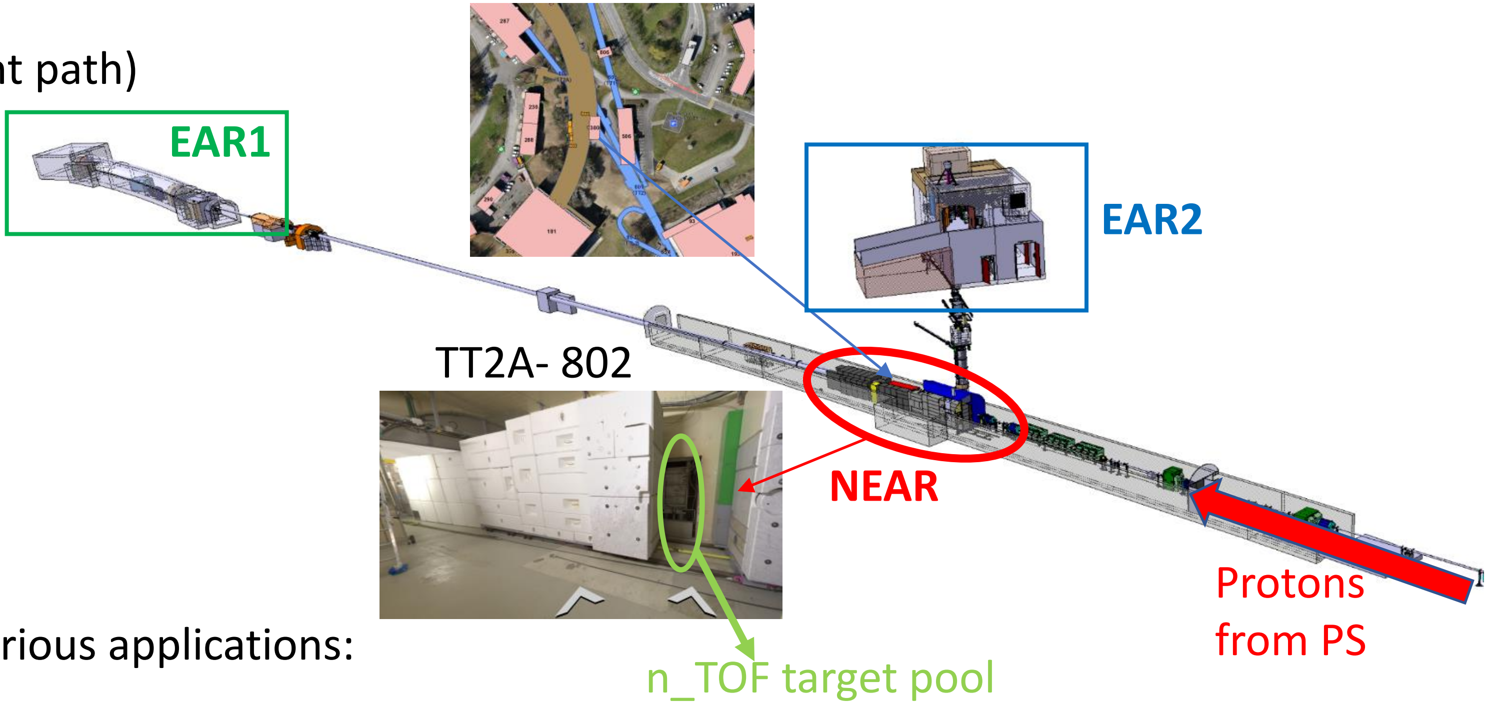
[4]Universidad de Sevilla, Spain

[5]University of Ioannina, Greece

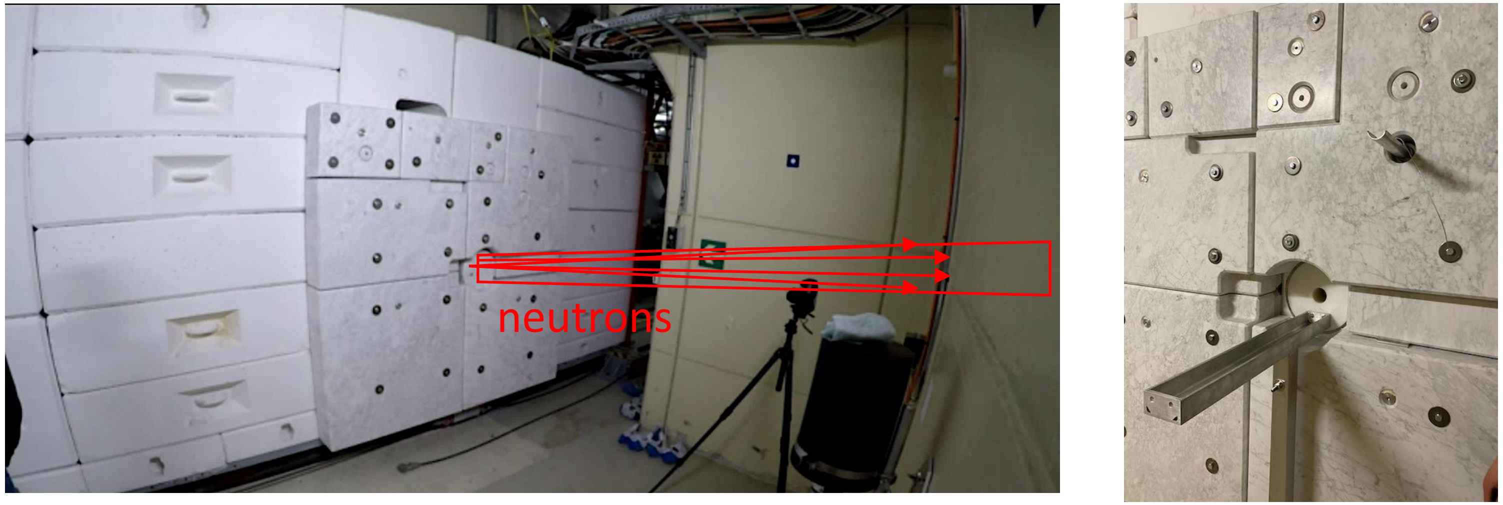
[6]www.cern.ch/n_TOF

The n_TOF NEAR station

- Very close to the Pb spallation target (~2m flight path)
- Commissioned in 2021



- **n_TOF mixed field irradiation station [4]** for various applications:



Photos from A.P. Bernardes presentation, n_TOF meeting 25/11/2021

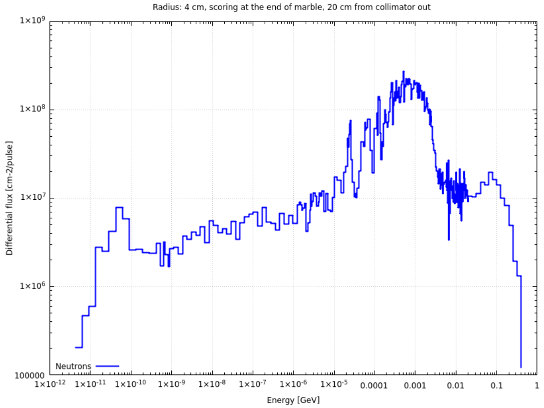
Possible applications [1-3]:

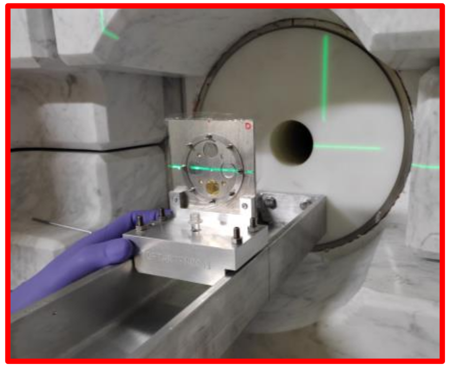
- Nuclear Astrophysics
- Nuclear energy production studies
- **Radiation damage studies** (conditions close to accelerator facilities)
- ……

[1] M. Cecchetto et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 70, NO. 8, AUGUST 2023
[2] A. Mengoni et al., CERN-INTC-2020-073; INTC-I-222 (2020)
[3] E. Stamati, et al., CERN-INTC-2022-008; INTC-P-623 (2022)
[4] M. Ferrari et al., Phys. Rev. Accel. Beams **25**, 103001 (2022)

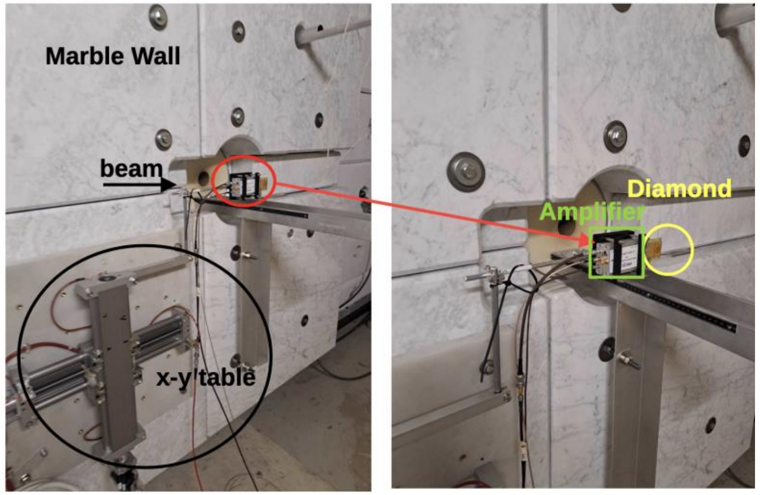
Commissioning of the NEAR station

1) Extensive Monte Carlo Simulations [1,4,5]
2) Multiple Foil Activation Analysis (MAM1 and MAM2 configurations) [5]
3) Moderation-Absorption technique (ANTILOPE) [5]





4) Active diamond detector measurement of fluence and profile [6,7,8]



[1] M. Cecchetto et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 70, NO. 8, AUGUST 2023
[4] M. Ferrari et al., Phys. Rev. Accel. Beams **25**, 103001 (2022)
[5[E. Stamati et al., EPJ Web of Conferences 284, 06009 (2023)
[6] M. Diakaki et al., CERN-INTC-2022-022 / INTC-P-631 (2022)
[7] K. Kaperoni et al., RAP CONFERENCE PROCEEDINGS, VOL. 8, PP. 79–83, 2023
[8] K. Kaperoni et al., Presentations at n_TOF Collaboration meetings

Active diamond detector measurements – Overview

- Diamond sensor + electronics **especially developed by CIVIDEC Instrumentation [9]** for the measurements at NEAR:
- ➢ Fast-response, high-radiation-hardness, high-resolution, low-noise radiation detector
- ➢ Single-crystal sensor fabricated via the CVD (Chemical Vapour Deposition) technology.
- ➢ **Characteristics**: 50 µm thickness, 4x4 mm^2 active surface *(Thin detector to cope with harsh NEAR conditions [10])*

[9] CIVIDEC Instrumentation, https://cividec.at/
[10] M. Angelone and C. Verona, J. Nucl. Eng. 2021, 2, 422–470

cividec
Instrumentation

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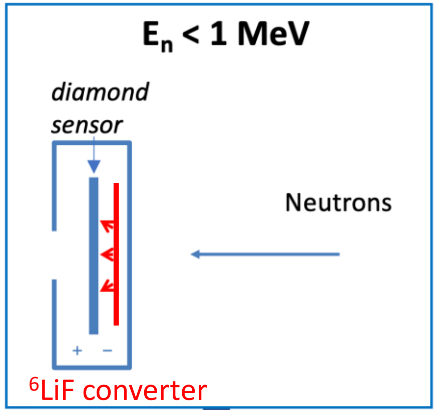
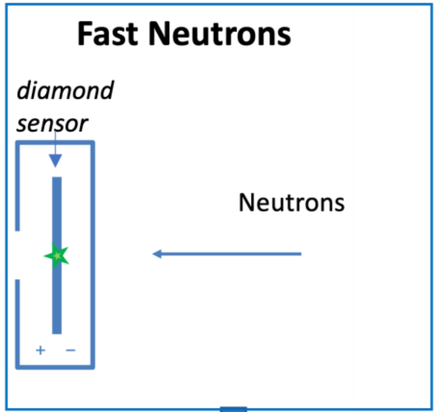
- **Neutron Detection Principle:**





based on a secondary reaction:
^{6}Li(n,t)^{4}He
Diamond sensor measures the secondary t and α particles

based on neutron interactions in the diamond:
^{12}C(n,el) and **^{12}C(n,inl)**
For E_n > 6MeV also **^{12,13}C(n,xα/p)**

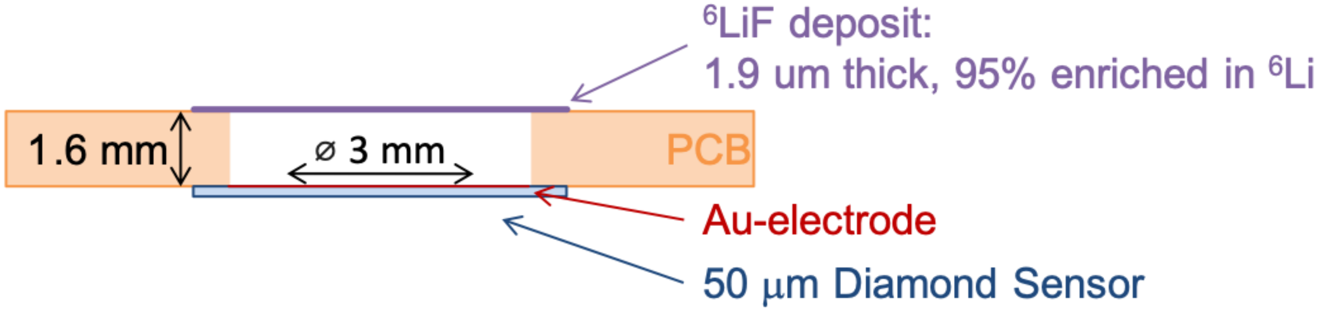
This principle already used in fission reactors and fusion tokamaks [10]

Nuclear reaction	E_{th} [MeV]	Q [MeV]
^{12}C(n,el)^{12}C	0.0	0.0
^{12}C(n,α)^{9}Be	6.2	-5.7
^{12}C(n,3α)	7.9	-7.3
^{12}C(n,p)^{12}B	13.6	-12.6
^{12}C(n,d)^{11}B	14.9	-13.7
^{13}C(n,α)^{10}Be	4.1	-3.8

[9] CIVIDEC Instrumentation, https://cividec.at/
[10] M. Angelone and C. Verona, J. Nucl. Eng. 2021, 2, 422–470

Active diamond detector measurements – Overview

- **Schematics of detector setup:**



^{6}LiF deposit:
1.9 um thick, 95% enriched in ^{6}Li

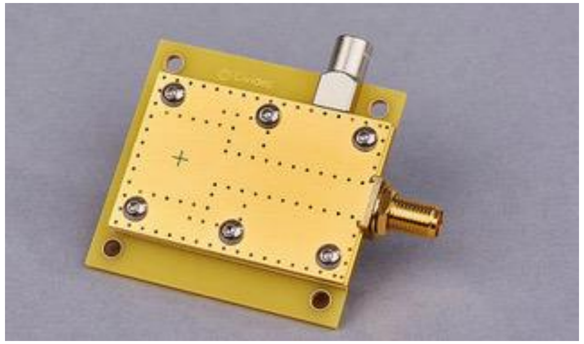
1.6 mm

⌀ 3 mm

PCB

Au-electrode

50 μm Diamond Sensor



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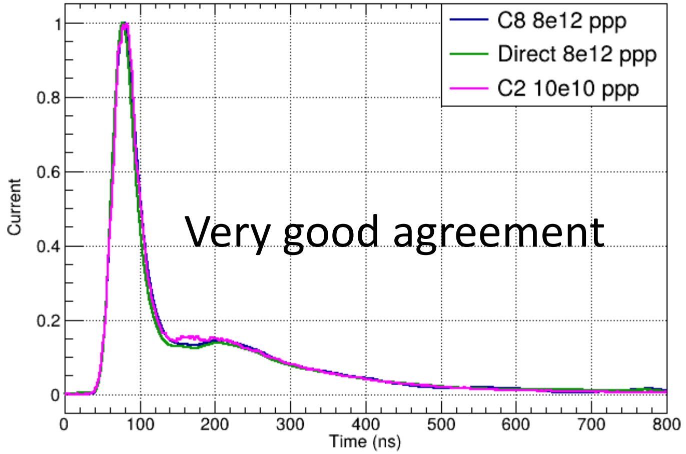
Instrumentation

- **Electronic / Readout setups used:**

A) 10 MHz DC-coupled amplifier (“C8”) : *Low gain, no saturation at g-flash: high neutron energies*
B) 2 GHz AC-coupled 40 dB amplifier (“C2”) : *High gain, very fast AC readout (pulse height mode) - no saturation for 10e10 ppp*
C) No preamplification stage (“Direct”) : *70 m cable betweeen detector and DAQ.*

A,B)

C)

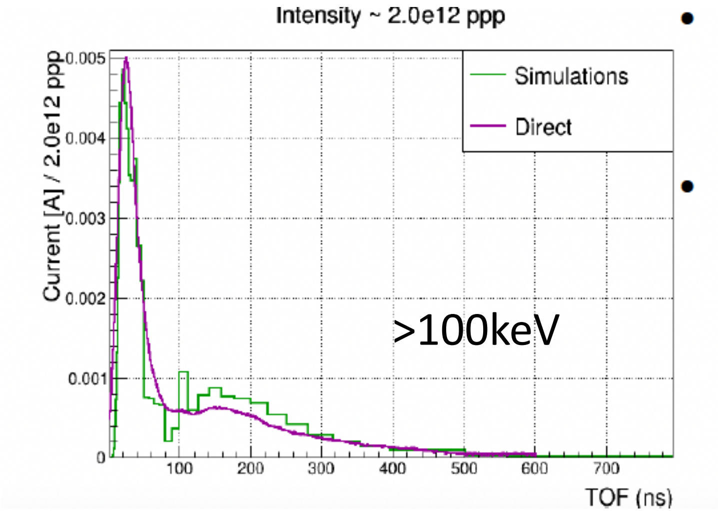


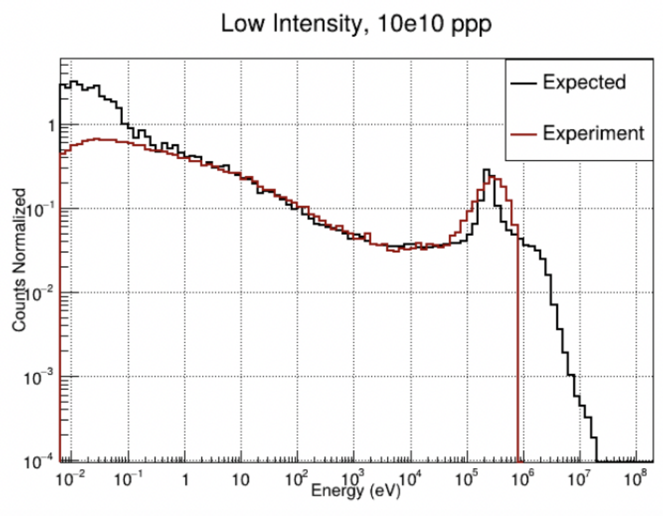
Very good agreement

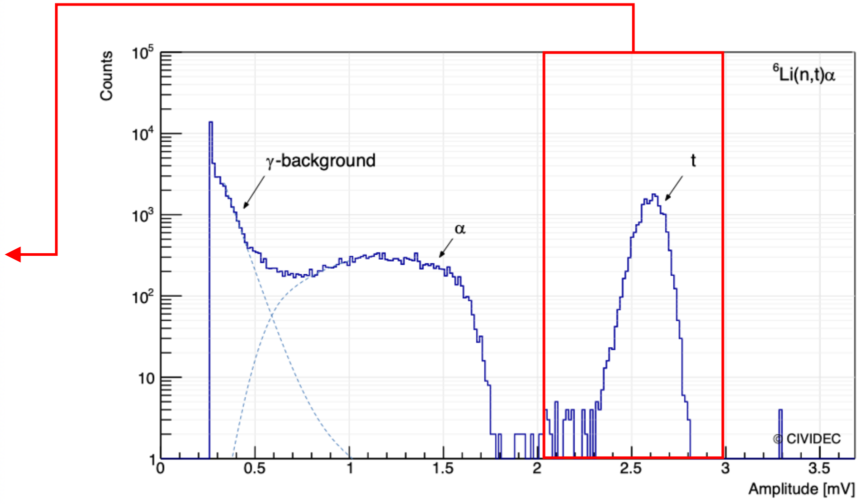
Active diamond detector measurements – Overview

- **Different configurations and measurements:**

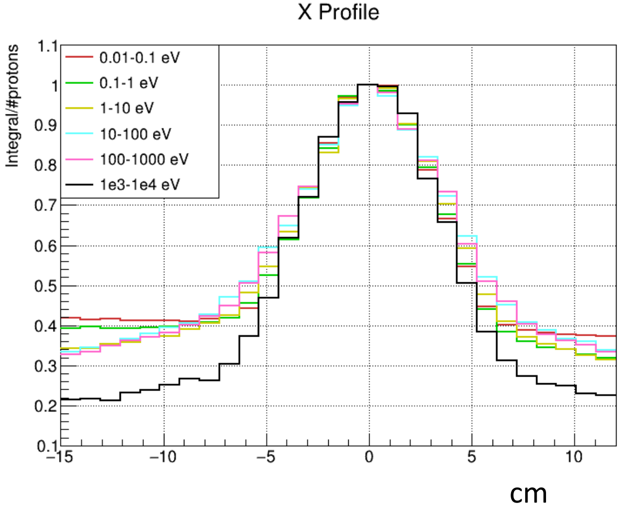
➢ **Neutron flux measurements:**

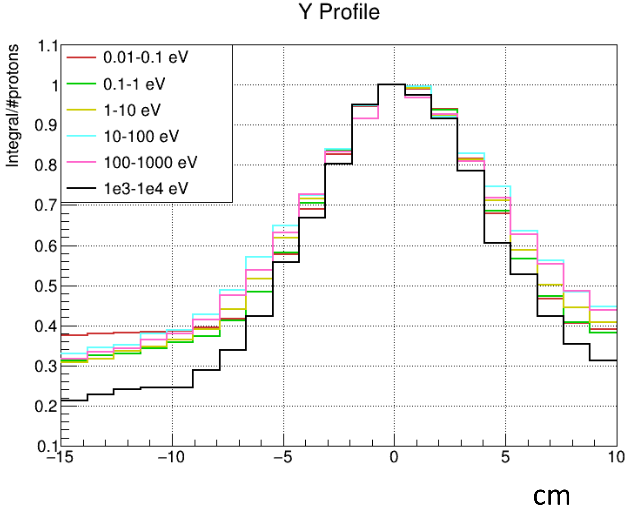






➢ **Neutron beam profile measurements:**





+ Other configurations:

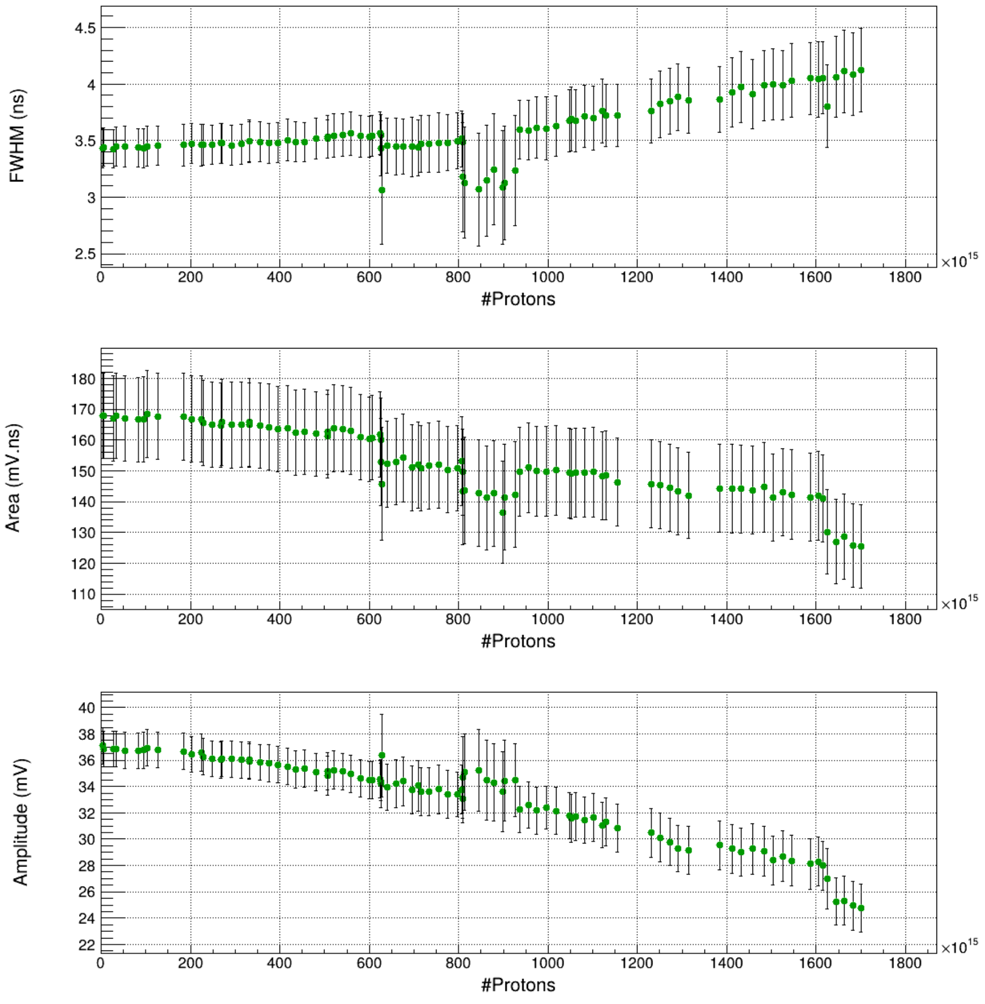
- 5mm B_4C filter
- Position close to the wall
- Au and Cd filters.

➢ Good preliminary results,

➢ Finalisation and Monte Carlo simulations ongoing.

Active diamond detector measurements – Overview

- **Interesting degradation of detector’s performances (C2):**



Campaign: August 2023

Deterioration of signal characteristics:
- Broadening of FWHM,
- Lowering of area
- Lowering of Amplitude

Typically due to radiation damage:
Defects of various types in the lattice, due to energetic recoil nuclei/ from nuclear collisions and reactions (vacancies and displaced atoms in interstitial sites, trapping - detrapping process, polarization effects [10]….)

All these effects have been / are currently being extensively studied for neutron irradiation on CVD diamonds due to their usage for neutron detection at various fields [10-11]

[10] M. Angelone and C. Verona, J. Nucl. Eng. 2021, 2, 422–470 *and ref therein*
[11] M. Passeri et al., Nuclear Inst. and Methods in Physics Research, A 1010 (2021) 165574 *and ref therein*

Why new measurements are needed ???

Interesting to study **radiation hardness of our thin sCVD detector** at the NEAR neutron field.

- Lifetime of diamond as neutron monitor at NEAR.
- General results on radiation damage of **50 µm sCVD** in **white neutron beam** from spallation source.
  Interesting for various applications using diamond detectors as neutron monitors – fission / fusion reactors, accelerator environments, atmospheric environments etc) (complete ongoing PhD work).

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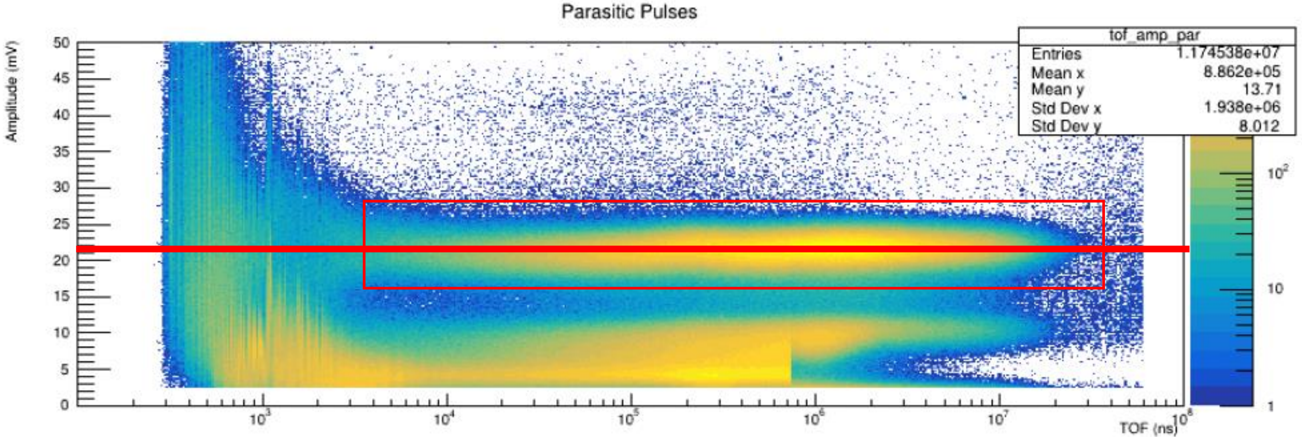
BUT : The data we collected with the **sCVD up to now are not sufficient**

1) Counting rate not reduced throughout the campaigns



=> No proper quantification of lifetime of sCVD as detector at NEAR

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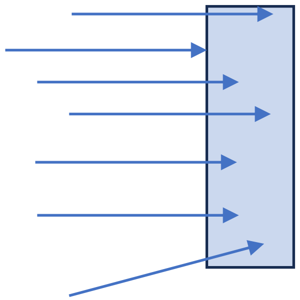
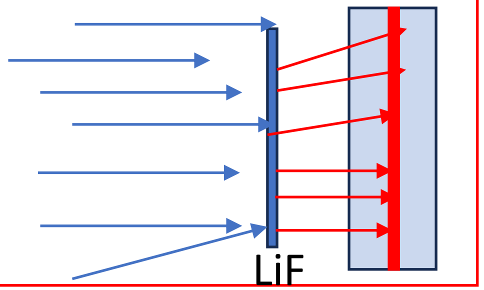
2) Two different sources of radiation damage:

a) Interaction of <u>fast neutrons</u>
=> recoil nuclei from elastic/inelastic scattering and other reactions ANYWHERE in the sensor
=> Homogeneous Radiation damage



b) Interaction of <u>slow neutrons</u>
=> alpha and triton recoils of the ^{6}Li(n,t)^{4}He reaction



=> No proper quantification of the two factors of radiation damage

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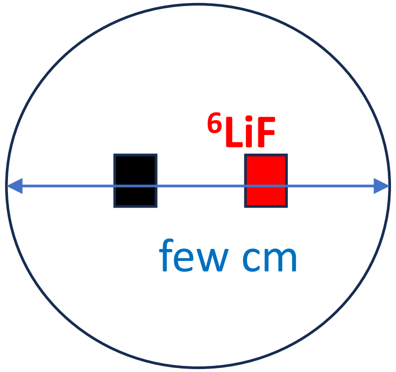
3) Data from different campaigns, with different characteristics

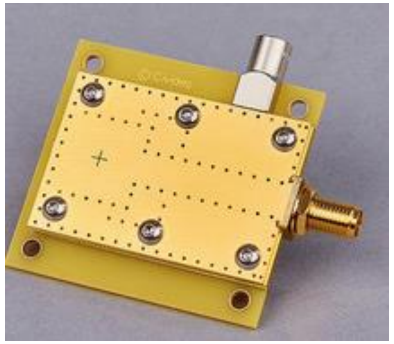
a) the setup slightly changed each time,
b) the neutron beam profile at NEAR was measured
c) the detector was used at other measurements (EAR1, EAR2)
=> conversion from protons on n_TOF target to neutrons on detector is not straightforward

=> not possible to combine all campaigns in one consistent study of radiation damage effects with respect to neutron dose

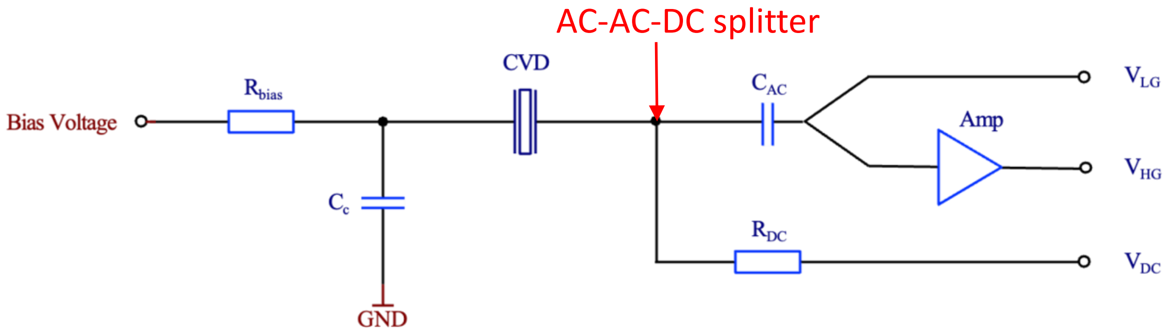
New experimental setup & proton request

- Propose to **measure with two 50 µm thick new diamond sensors <u>IN PARALLEL</u>**, one **with** and one **without ^{6}LiF converter (=> disentangle the two sources of radiation damage)**
- Same neutron irradiation conditions (few cm flat top profile)





- For each detector the following electronics setup proposed:



=> Three readouts in parallel in order to combine **maximum possible information in-beam**:

V_{LG}: AC output without amplification (high neutron energy region)

V_{HG}: AC output with amplification (low neutron energy region - signals from the ^{6}Li(n,t) reaction)

V_{DC}: DC measurement of the **dark current** of the sensor

First time such a combined readout scheme implemented for monitoring of Radiation Damage vs Neutron Dose .

New experimental setup & proton request

After the end of the irradiation campaign, **Electron Paramagnetic Resonance (EPR) spectroscopy** measurements will be performed at the NSCR “Demokritos”, Greece [12,13] for an offline study of the structure defects.

BEAM TIME ESTIMATION (sCVD): continuous campaign with 6×10^{18} protons estimated to be sufficient to reach the point where the tritons’ pulse height ~ background.

[12] M. Kokkoris et al., Nucl. Inst. and Methods in Phys. Res. B 195 (2002) 414–421

[13] G. Mitrikas, M. Kokkoris et al., Eur. Phys. J. AP 21, 163–170 (2003)

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EXTENSION OF THE PROPOSED RADIATION DAMAGE STUDY TO SiC:
Interesting to study **radiation hardness of SiC sensor** of the same thickness under the same conditions [14,15], which is also a very important material used in electronics and is interesting for future applications (mainly accelerator environments – high energy physics at CERN)
=> **Replicate the proposed setup for sCVD and run at a different campaign**

BEAM TIME ESTIMATION (SiC): continuous campaign with 6×10^{18} protons estimated to be sufficient.

[12] M. Kokkoris et al., Nucl. Inst. and Methods in Phys. Res. B 195 (2002) 414–421

[13] G. Mitrikas, M. Kokkoris et al., Eur. Phys. J. AP 21, 163–170 (2003)

[14] T. Gaggl et al., Nucl. Inst. and Methods in Phys. Res. A 1040 (2022) 167218

[15] A. Gospner et al., 2023 JINST 18 C11027

Conclusion

- We propose a systematic study of

a) The lifetime of a **50 µm sCVD diamond sensor** as neutron monitor at NEAR.

b) The two different components of the radiation damage (fast neutrons=> homogeneous , slow neutrons => “layer”)

c) Record the **detector performance vs increasing radiation** with three different readouts => combine the maximum information possible.

d) Offline study of the crystal defects with **Electron Paramagnetic Resonance (EPR) spectroscopy**

- The same study is proposed for a **50 µm thick SiC sensor** in order to compare the two materials' performance in the harsh environment of NEAR.

Proton request:

sCVD:
6×10^{18} protons

SiC:
6×10^{18} protons

Total: 1.2×10^{19} protons requested in two campaigns

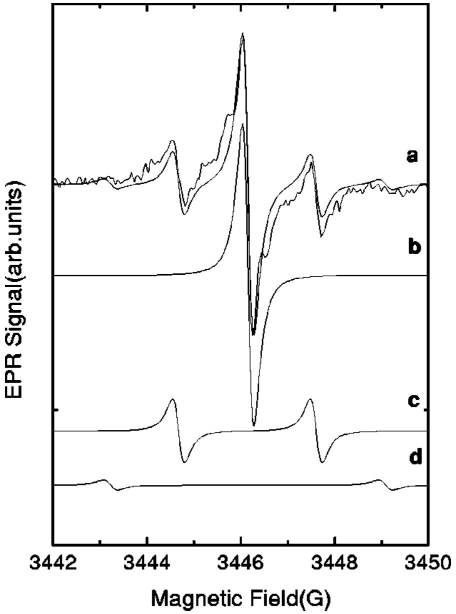
Thank you!

Extra slides

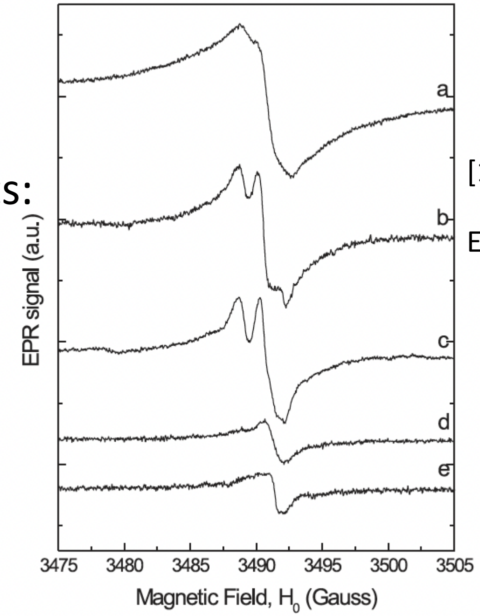
EPR

- An EPR spectrum is usually directly measured as the first derivative of the absorption resonance of microwave radiation. The microwave is kept at a fixed frequency and the magnetic field is swept. For a specific microwave frequency (with energy hv), a resonance occurs at a magnetic field of $B=hv/g_e\mu_{B,}$ for free electrons. When the electron is not free $B=hv/g\mu_B$, where g different to g_e , which means that the electron has gained or lost angular momentum through spin–orbit coupling, and the value of g that occurs from the EPR measurement (since hv is known, μ_B is known and B is estimated as the position of the resonance (i.e. the value of B where the derivative is 0) gives information about the nature of the atomic or molecular orbital (in our case from defects) containing the unpaired electron.
- Example of EPR measurement of different defects created from the irradiation of 12 MeV protons ins 300 um SiC wafers (taken from *H. J. von Bardeleben et al., PHYSICAL REVIEW B, VOLUME 62, NUMBER 15 (2000): "Proton-implantation-induced defects in n-type 6H- and 4H-SiC: An electron paramagnetic resonance study"):*

Trace region:

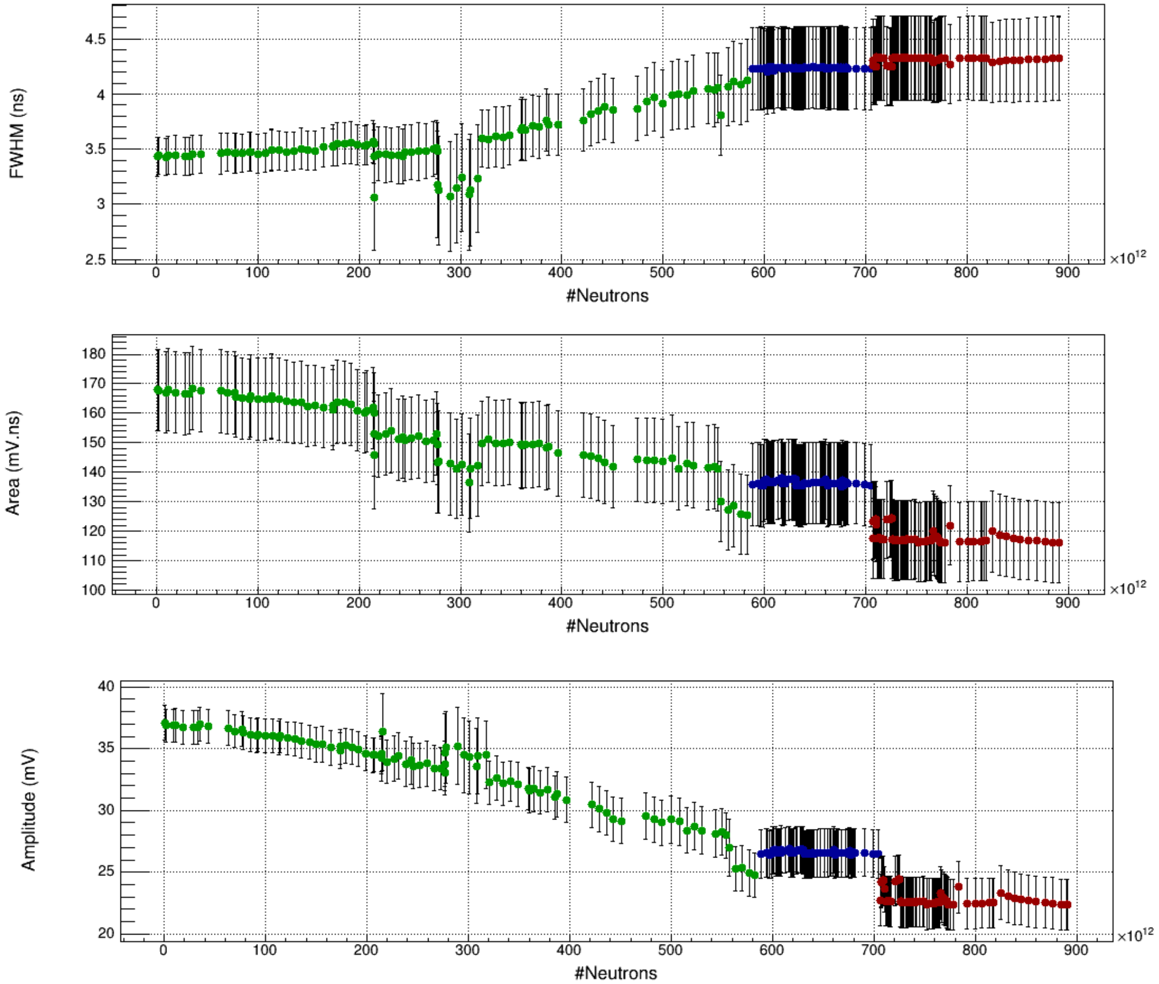


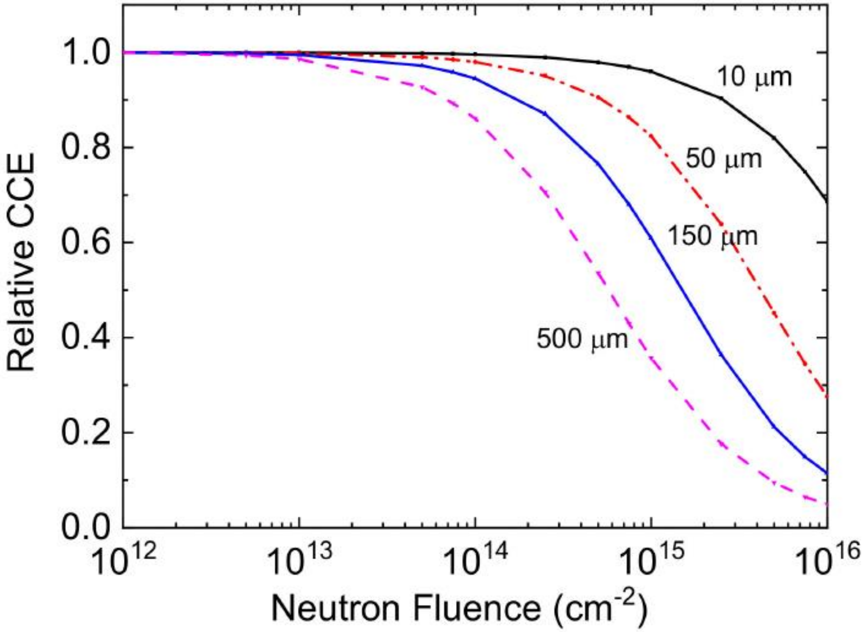
End-of-range defects: "cluster" defects



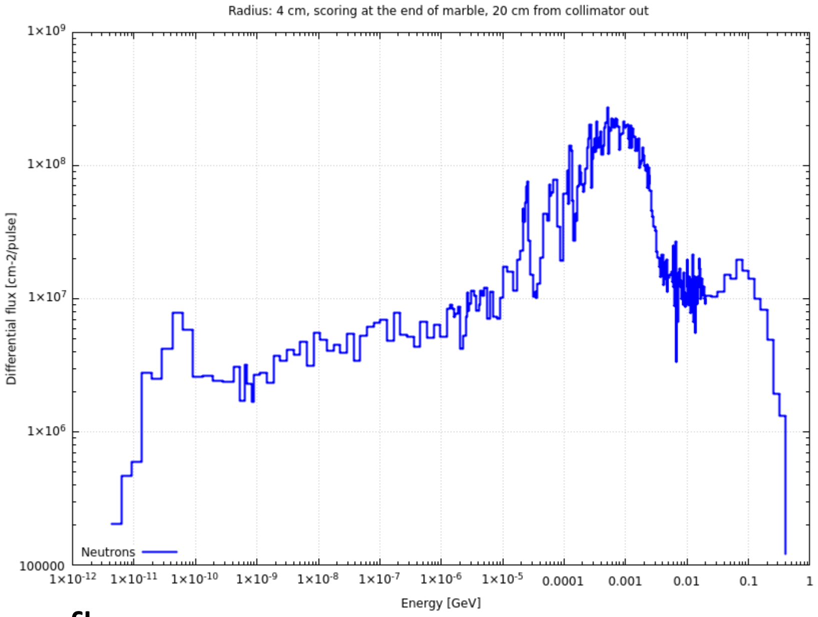
[13] G. Mitrikas, M. Kokkoris et al.,

Eur. Phys. J. AP 21, 163–170 (2003)

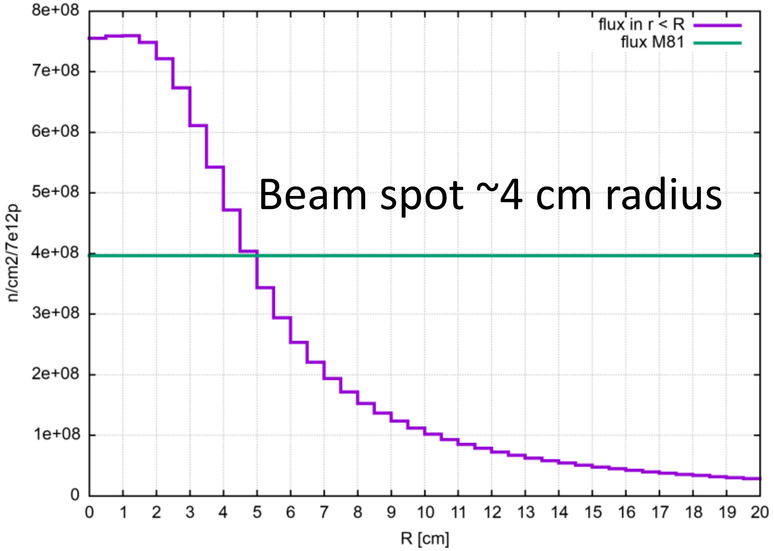

FWHM (ns)
2.5
3
3.5
4
4.5
Area (mV.ns)
100
110
120
130
140
150
160
170
180
Amplitude (mV)
20
25
30
35
40
0
100
200
300
400
500
600
700
800
900
×10¹²
#Neutrons


Relative CCE
0.0
0.2
0.4
0.6
0.8
1.0
10 μm
50 μm
150 μm
500 μm
10¹²
10¹³
10¹⁴
10¹⁵
10¹⁶
Neutron Fluence (cm⁻²)

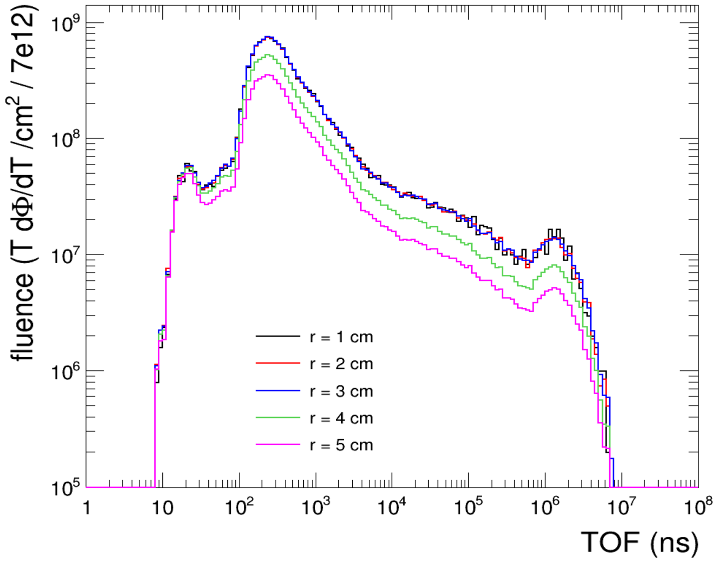
NEUTRON FLUENCE CHARACTERISATION at NEAR (simulations)



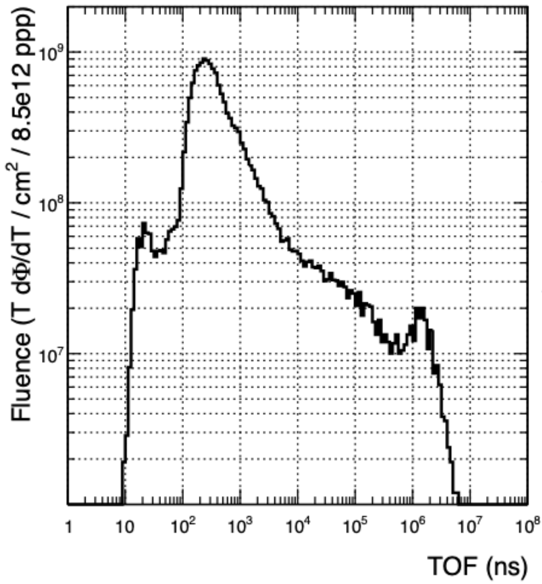
Radial dependence of neutron fluence:



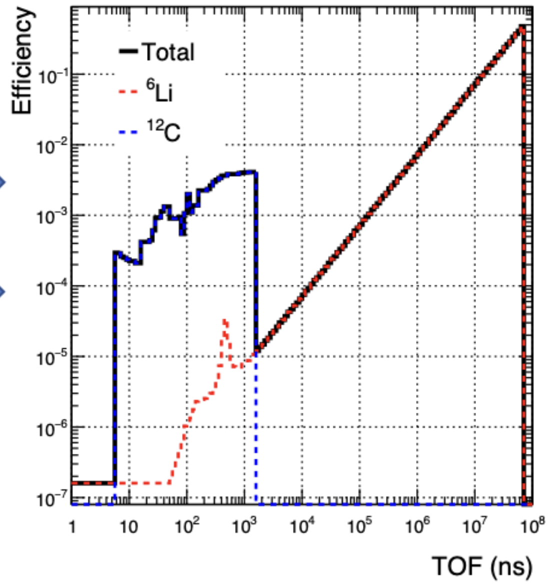
Beam spot ~4 cm radius



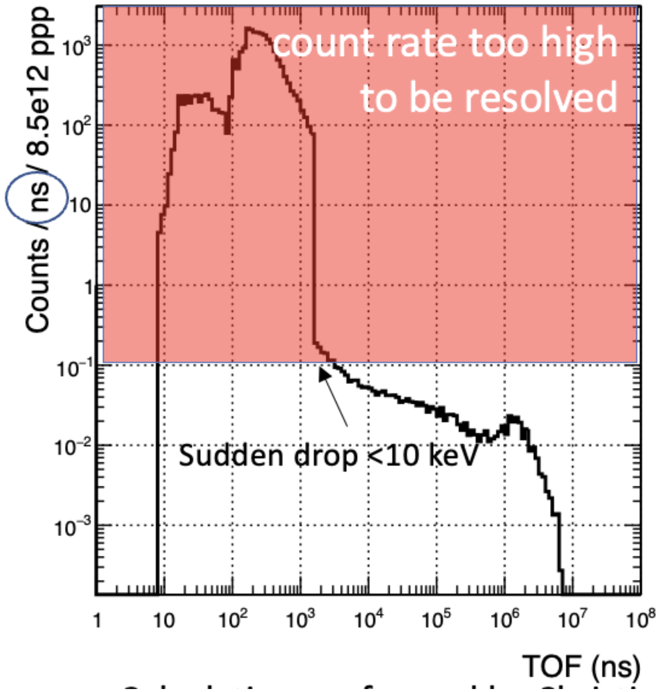
FLUKA simulations of neutron flux
(scaled to detector area, converted to neutron rate)



Neutron detection efficiency vs neutron energy (simulations)

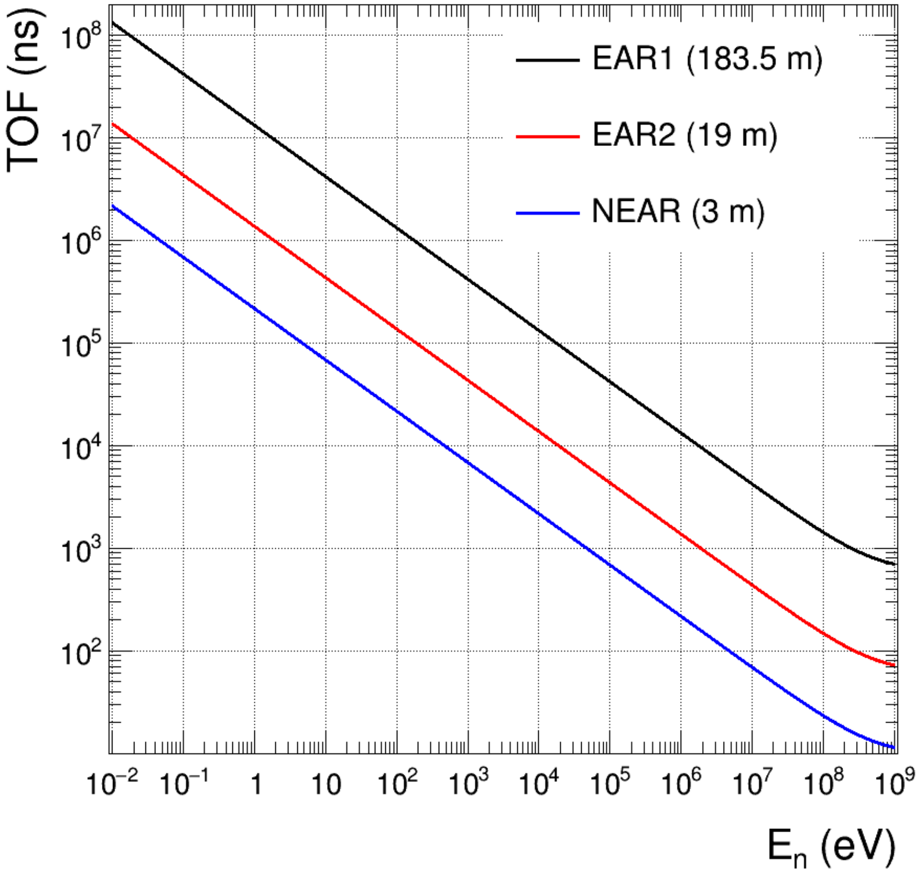


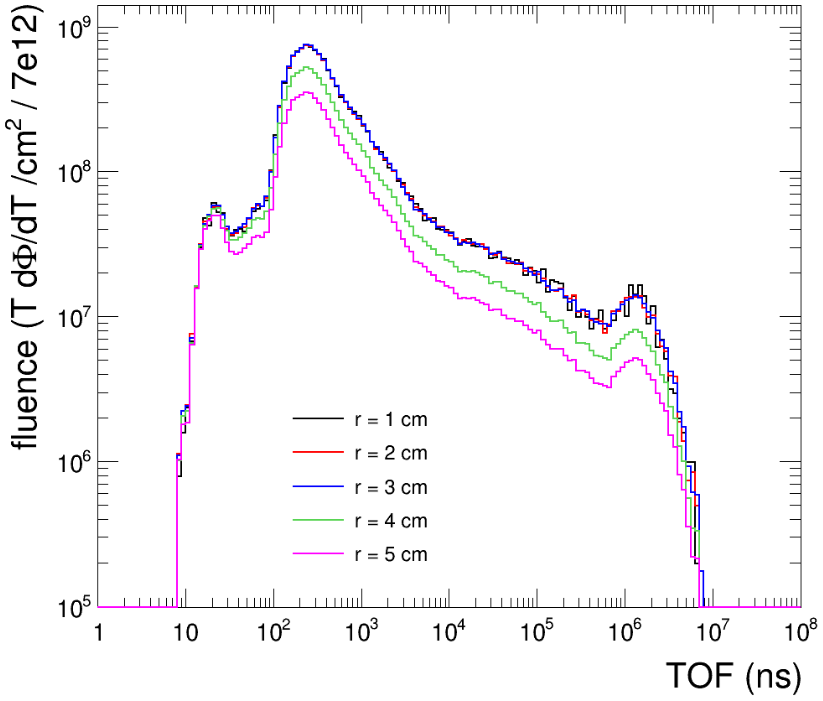
Counting Rate:



count rate too high to be resolved

Sudden drop <10 keV


TOF (ns)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
EAR1 (183.5 m)
EAR2 (19 m)
NEAR (3 m)
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
E_n (eV)


fluence (T dΦ/dT /cm^2 / 7e12)
10^9
10^8
10^7
10^6
10^5
r = 1 cm
r = 2 cm
r = 3 cm
r = 4 cm
r = 5 cm
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
TOF (ns)

Conversion yield

Energy Interval	ε (ENDF/B-VIII.0)	Q_μ [fC]
$E_n < 10$ keV	^{6}Li(n,a)t	Q-value/2/E_{ion}*q_{el} = 29.4 fC
10 keV < E_n < 1 MeV	^{6}Li(n,a)t ^{12}C(n,tot)	Q-value/2/E_{ion}*q_{el} = 29.4 fC $f_1(E_n)$, see below
E_n > 1 MeV	^{12}C(n,tot)	$f_2(E_n)$, Geant4 P. Kavrigin

ionisation energy of diamond

elementary charge

$$f_1(E_n) = \underbrace{E_n * 0.286}_{E_{max} \text{ for } ^{12}\text{C nucleus in } ^{12}\text{C(n,el)}} / E_{ion} * q_{el} * 0.5$$

assuming isotropic scattering, we measure on average ½ of the total charge

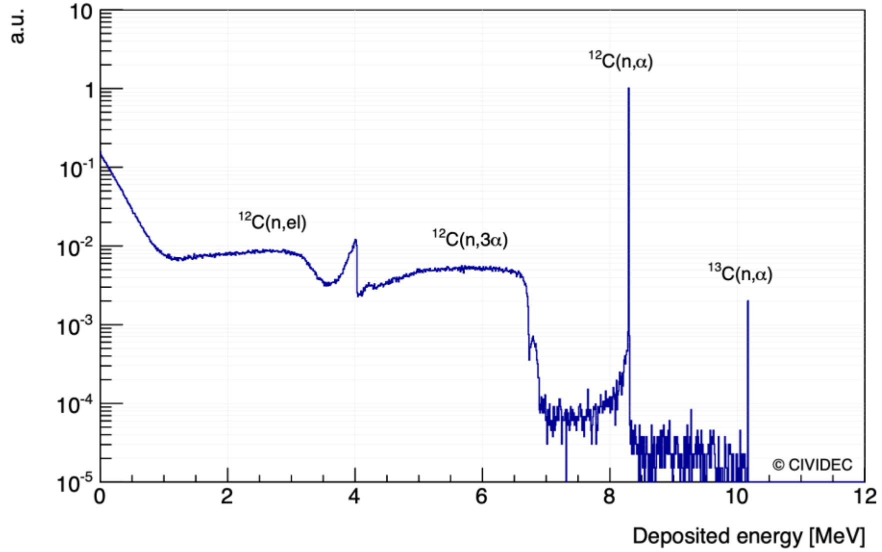


Figure 3.23: Deposited energy spectrum of 14 MeV neutrons in 500 μm diamond.

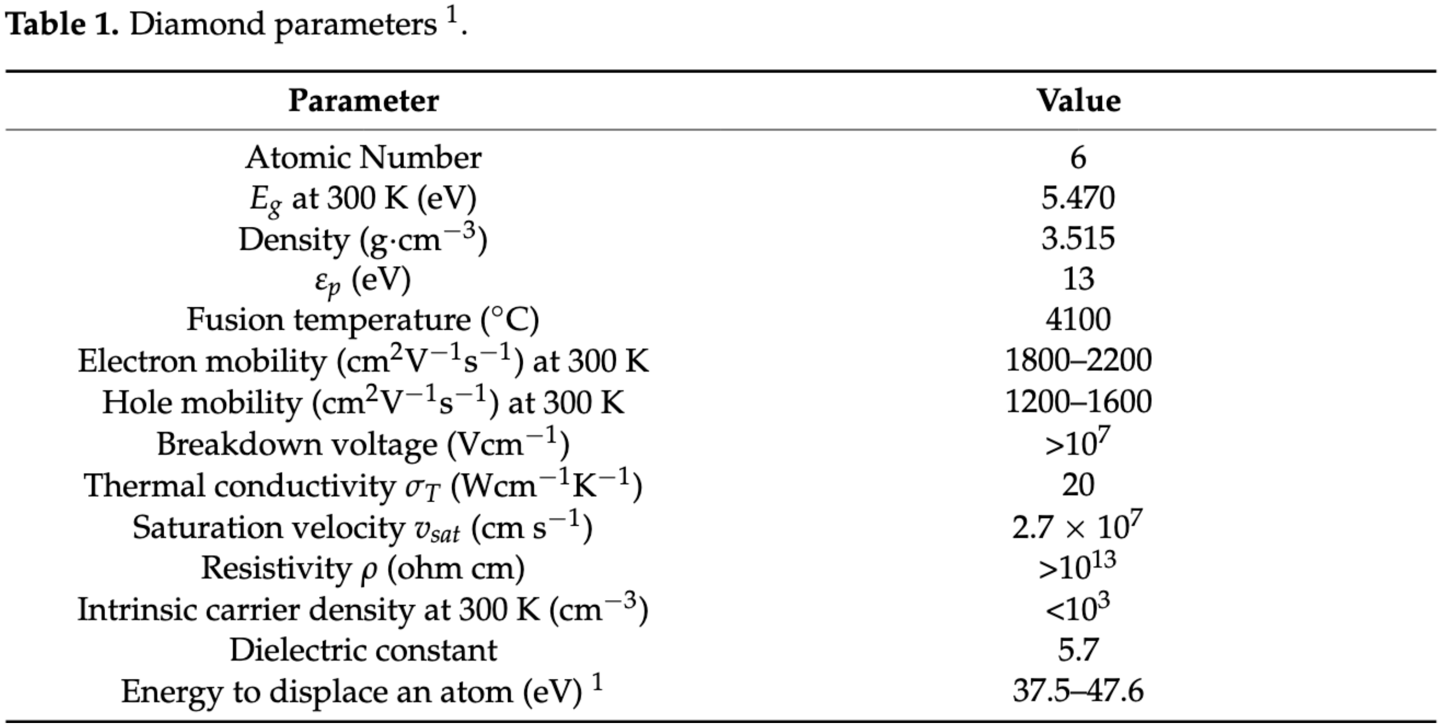


Table 1. Diamond parameters [1].

Parameter	Value
Atomic Number	6
E_g at 300 K (eV)	5.470
Density (g·cm^{-3})	3.515
ε_p (eV)	13
Fusion temperature (°C)	4100
Electron mobility (cm^{2}V^{-1}s^{-1}) at 300 K	1800–2200
Hole mobility (cm^{2}V^{-1}s^{-1}) at 300 K	1200–1600
Breakdown voltage (Vcm^{-1})	$>10^7$
Thermal conductivity σ_T (Wcm^{-1}K^{-1})	20
Saturation velocity v_{sat} (cm s^{-1})	2.7×10^7
Resistivity ρ (ohm cm)	$>10^{13}$
Intrinsic carrier density at 300 K (cm^{-3})	$<10^3$
Dielectric constant	5.7
Energy to displace an atom (eV) [1]	37.5–47.6

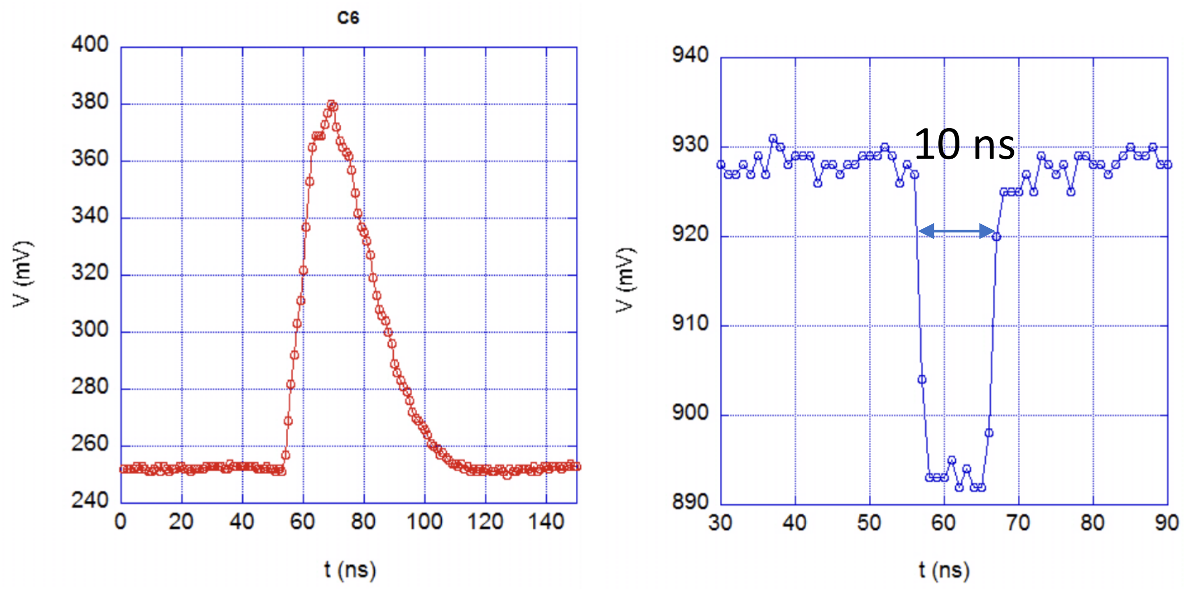


Figure 1. Alpha particle signals recorded with a SDD using CIVIDEC C6 (on the left) and C2 (on the right) preamplifiers.

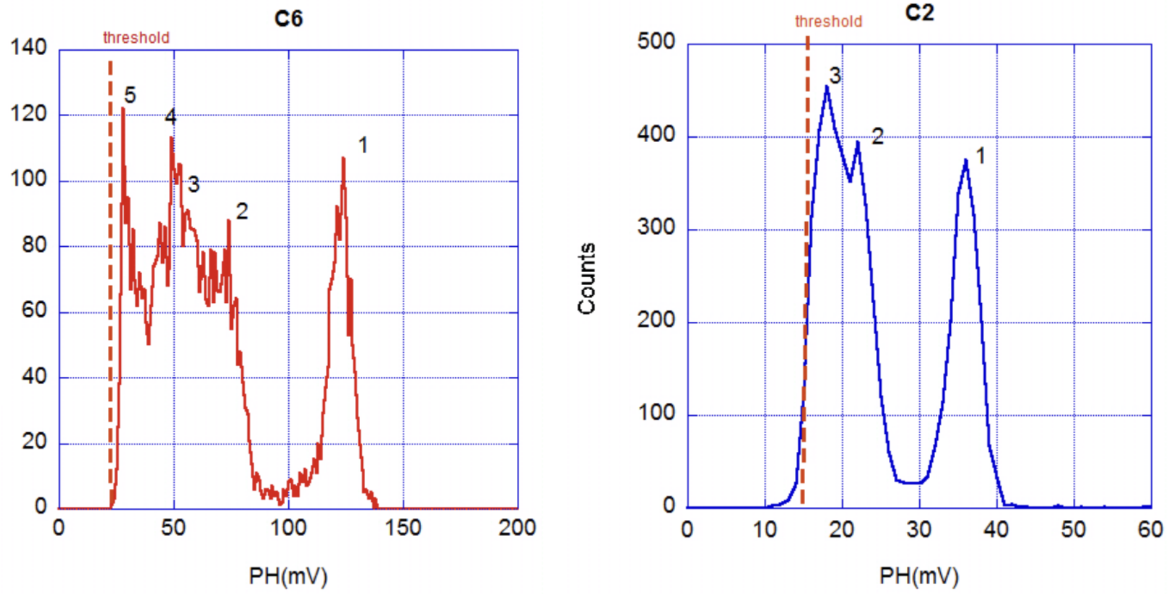
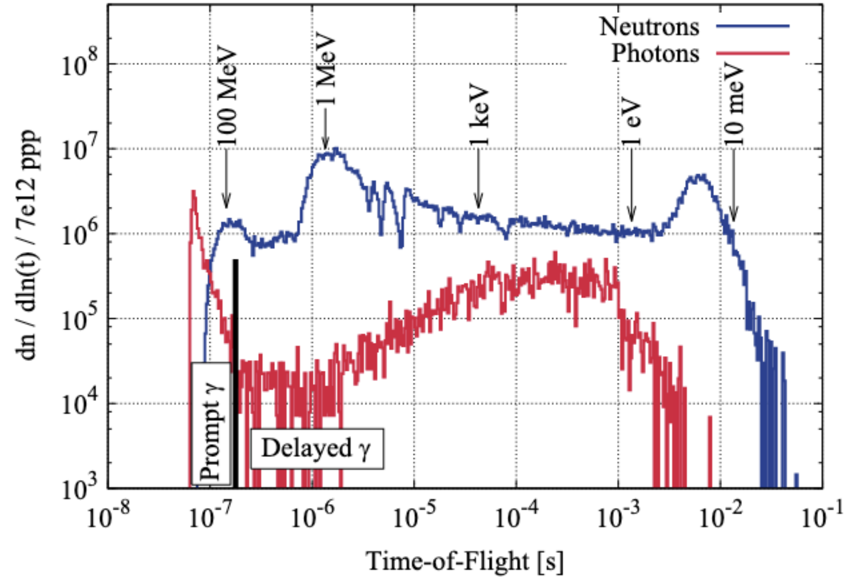


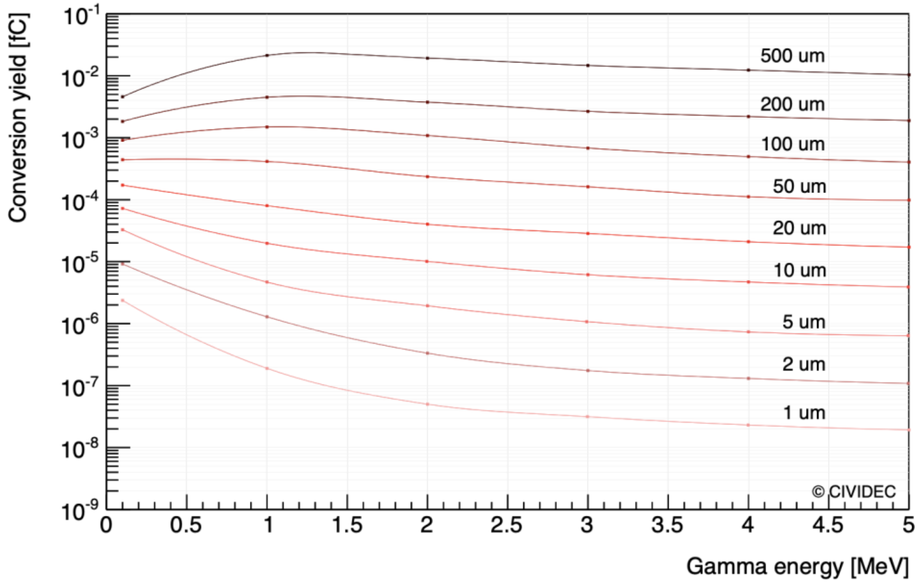
Figure 2. Pulse Height Spectra of an alpha source of Ra-226 recorded with a SDD using CIVIDEC C6 (on the left) and C2 (on the right) preamplifiers. Numbers from 1 to 5 tag the peaks as in table 1. A dashed vertical line indicates the acquisition threshold.

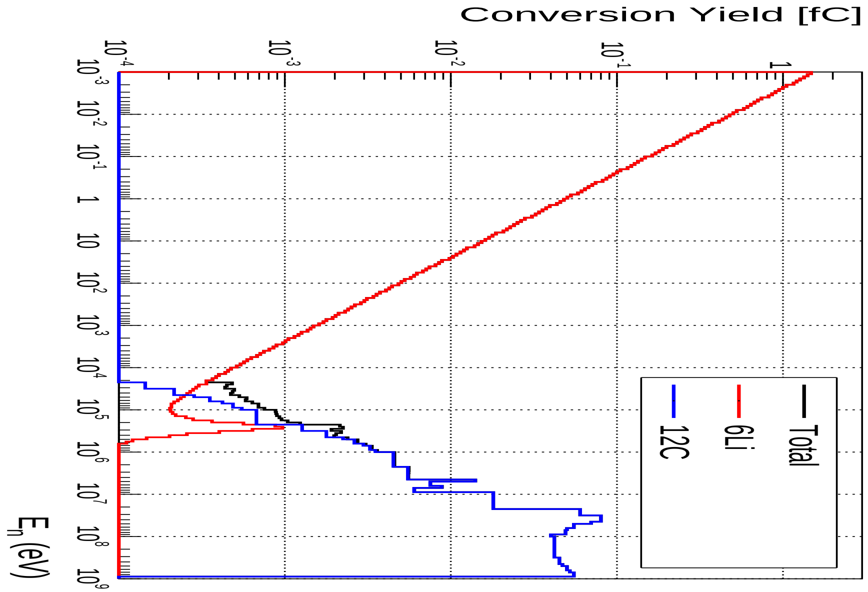
From Cazzaniga et al., 2016 JINST 11 P07012

Gamma background, grossier estimation from EAR2 simulations



In Figure 3.17 the conversion yield of the γ interaction in diamond is shown.



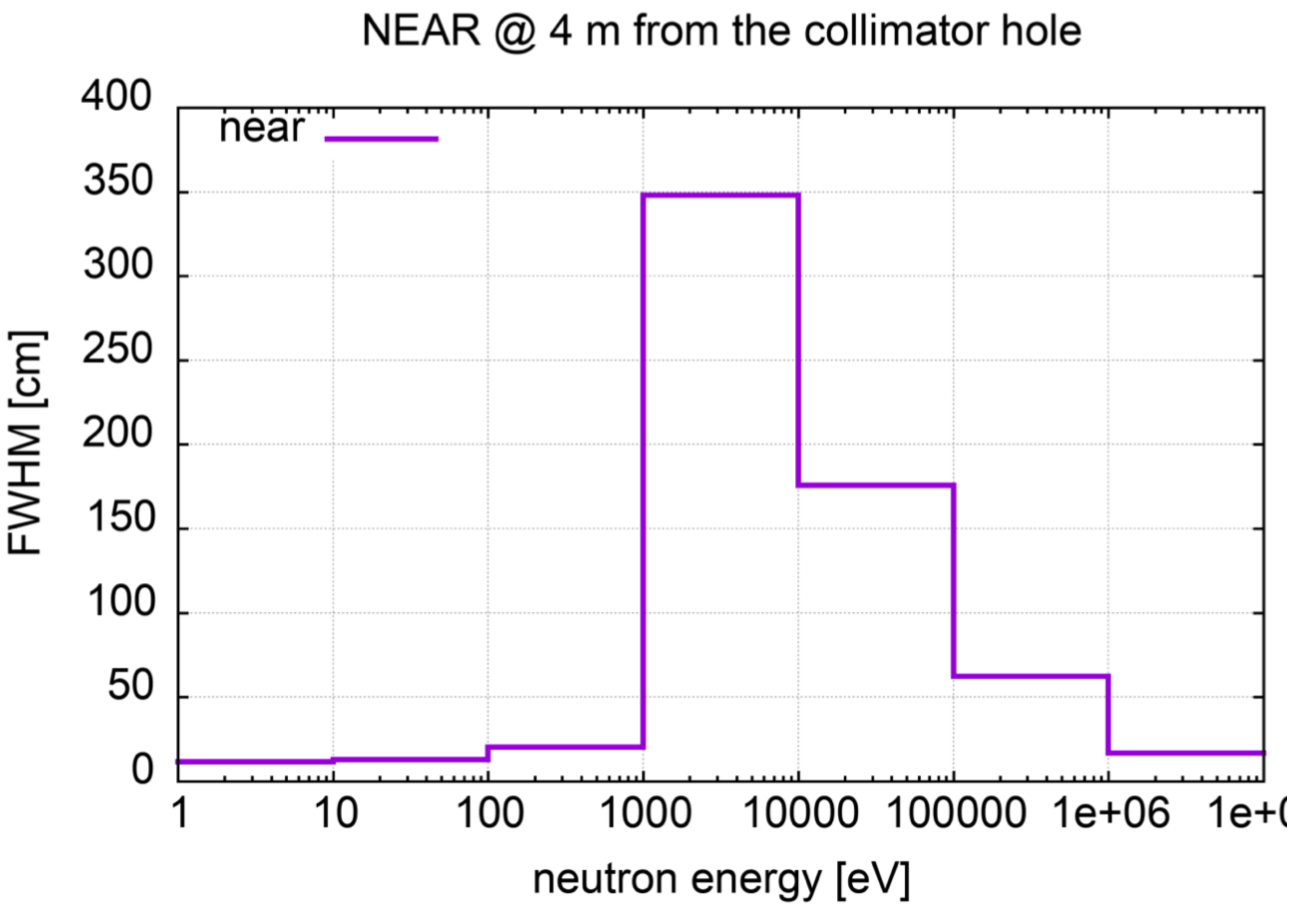


Delayed gammas not expected to significantly influence the measurement

Resolution for TOF measurements at NEAR

NEAR

Flight_path assumed: 4m


NEAR @ 4 m from the collimator hole

```
#area                : data/NEAR_score
#flight-path [cm] :        400.0
# energy range [eV]              FWHM [cm]    FWTM [cm]      dE/E
       1.0         10.0             11.7         39.0       5.8e-02
      10.0        100.0             13.0         45.7       6.5e-02
     100.0       1000.0             20.2        197.6       1.0e-01
    1000.0      10000.0            390.6        577.5       2.0e+00
   10000.0     100000.0            175.8        483.5       8.8e-01
  100000.0    1000000.0             62.4        157.8       3.1e-01
 1000000.0   10000000.0             16.6         48.3       8.3e-02
```

```
#area                : data/EAR2_scorewin
#flight-path [cm] :      2000.0
# energy range [eV]            FWHM [cm]   FWTM [cm]      dE/E
       0.1          1.0           3.5        15.3      3.5e-03
       1.0         10.0           3.9         9.2      3.9e-03
      10.0        100.0           4.2        11.3      4.2e-03
     100.0       1000.0           5.4        15.9      5.4e-03
    1000.0      10000.0          10.1        31.9      1.0e-02
   10000.0     100000.0          24.3        87.8      2.4e-02
  100000.0    1000000.0          63.4       154.7      6.3e-02
 1000000.0   10000000.0          27.2        74.7      2.7e-02
```

From the presentation of A. Mengoni, n_TOF collaboration meeting, 30-31 May 2022