Neutron spectrometer based on diamond detectors for fast reactors

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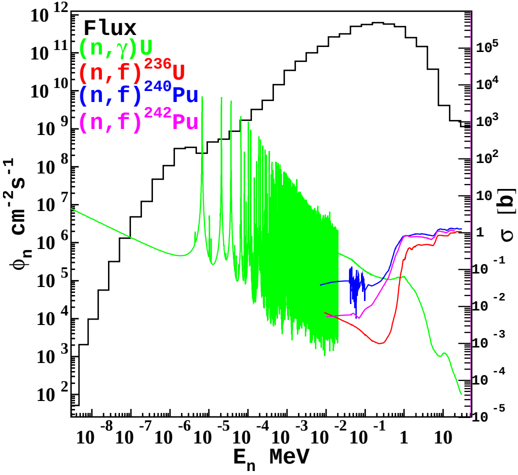
Fast Reactors

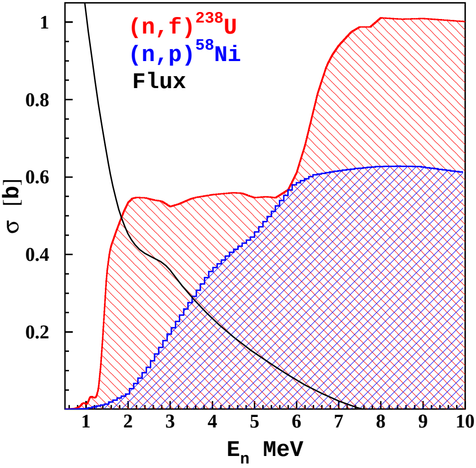
1. critical: PHENIX, SuperPHENIX, BN-600, BN-800 etc.,
2. subcritical: MUSE, GUINEVERE etc.,
3. future: ASTRID, BN-1200, BREST-300, MYRRHA etc.



- *Breeding* and *transmutation* to solve fuel shortage and radiotoxic waste problems.
- *Neutron spectrum* affects reactor characteristics.
- *Neutron spectrum* affects radiotoxic waste build-up rate.

Standard Diagnostics

1. Fission chambers with non-fissile deposits (e.g. ^{238}U),
2. activation foils producing relatively long lived isotopes/levels, e.g. by (n,p) reaction.



- counting rate/activity of isotope i:

$$A_i \simeq \int_{E_i^{th}}^{\infty} \Sigma(E_n)\phi_n(E_n)dE_n \ ,$$

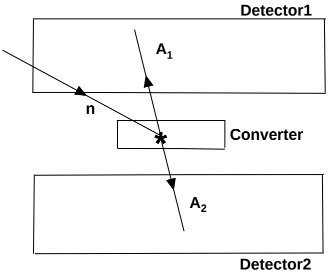
- system of N integral equations with different threshold energies E_i^{th} is solved with respect to $\phi_n(E_n)$,
- solution is obtained by unfolding codes like SAND.

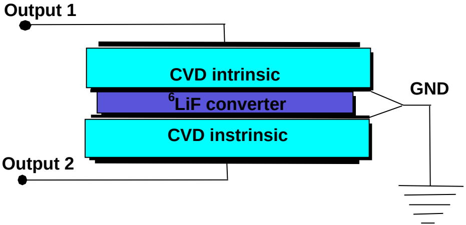
Single n Spectrometer for $E_n < 7$ MeV

Fission spectrum < 6 MeV, exothermic reactions ($Q = 4.79$ MeV) with charged products only:

$n +^6 Li \rightarrow t(2.73MeV) + \alpha(2.06MeV)$

1. event-by-event neutron energy: $E_n = E_{A_1} + E_{A_2} - Q$,
2. fast (60 ns) coincidence rejects noise,
3. high threshold $E_{th} > Q$, removes background,
4. (n,d)^{6}Li reaction contributes for $E_n > 3_{kin.} + 4_{th.}$ MeV,
5. (n,α)^{12}C reaction dominates at $E_n > 6_{kin.} + 4_{th.}$ MeV.





Diamond Detector vs. Gas Proportional Counter

Gas filled detectors are slow, bulky, but harder:

	Proportional Counter	Diamond Detector
Charge Mobility	0.3-0.4 cm^2/V/s	2000 cm^2/V/s
Charge Collection time	5-7 μs	2-10 ns
Counting Rate	20 kHz	10 MHz
Converter	H, ^{3}He, ^{10}B	H, ^{6}Li, ^{10}B
Energy loss	0.35 MeV/cm/bar	392 MeV/cm
Range at 7 MeV	60 cm/bar	150 μm
Size	10 cm	2 mm
Radiation hardness	very high	$< 10^{16}$ n/cm^2

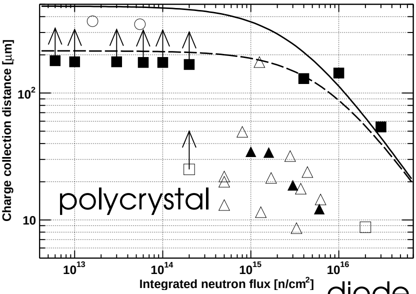
Comparison with Silicon detector:

- factor $\times$4-10 lower radiation damage ($\sigma_{C(n,n')} \times Z_C^2 \rho_C$),
- no intrinsic noise at high temperature ($E_g = 5.5$ eV).

Radiation Hardness to Fast Neutrons

Experimental studies of diamond RH concluded:

1. E6 single crystal has best RH,
2. 50 μm thick diamond will lose 10 % of the signal after 3×10^{16} n/cm^2,
3. diode-like single crystal detectors give significantly lower CCD, probably due to faster damage of p-type layer,
4. polycrystalline sensors feature order of magnitude lower CCD, but similar damage rate.

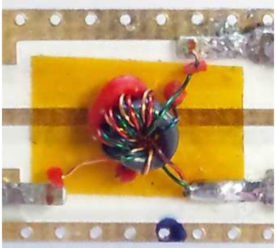


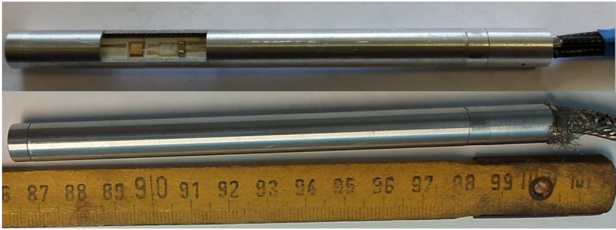
arxiv.org/1510.05415

For comparison, Silicon detectors maintain 100% CCE up to fluence of 10^{14} n/cm^2.

2016 Spectrometer Prototype

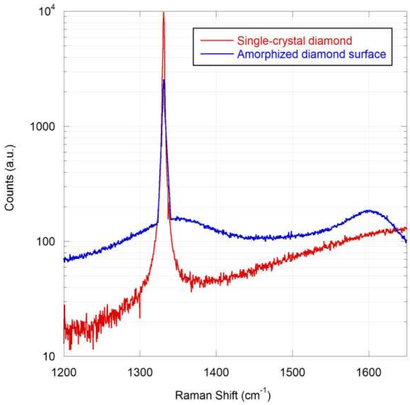
- Electronic grade E6 single crystal CVD diamonds,
- intrinsic-only of thickness 300 μm,
- almost ohmic contacts deposited by D. Trucchi at CNR-ISM (Monterotondo),
- local RF transformer pre-amplification,
- cylindrical aluminum case $D = 1$ cm and 13 cm long,
- additional cable shielding wire braid.

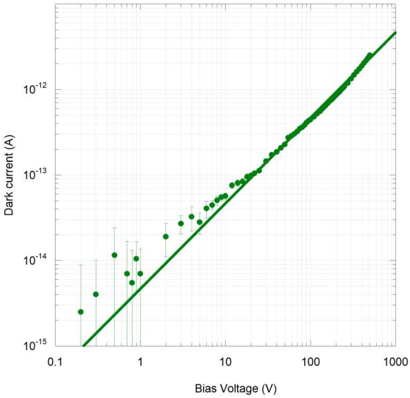




Diamond Metallization (D. Trucchi at CNR-ISM)

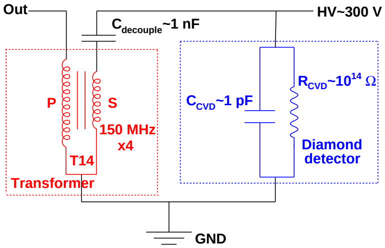
- graphitization of the surface before metallization,
- DLC sp2 bonds seen by Raman and XPS spectroscopy,
- thin DLC layer (< 3 nm) with resistivity 10^8 Ωcm,
- almost ohmic I(V) behavior (thin barrier).

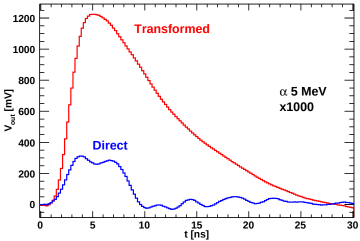




Local Preamplification

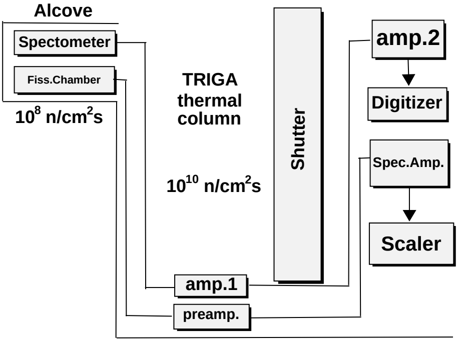
- Si-based electronics cannot be used near to detector in reactor core (less rad.hard than diamond),
- diamond is an almost ideal current source,
- 3-5 m long cable before the first amplifier,
- 150 MHz RF transformer integrates ($\tau_{LR} \sim 10$ ns) and amplifies ($\times 4$) the signal locally improving S/N.

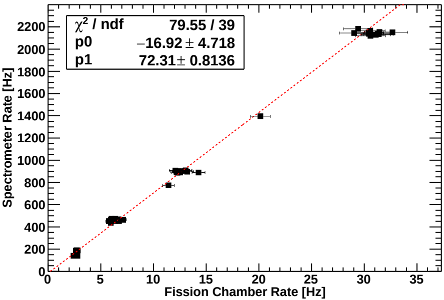




Experiment at TRIGA (LENA, Pavia)

- Spectrometer was installed in the low flux alcove of TRIGA graphite thermal column,
- neutron flux was up to 10^8 n/cm^{2}s at 250 kW,
- calibrated FC located at 1 cm distance,
- reactor power varied in range 20-250 kW,
- about 100 runs with 6×10^4 events each recorded.

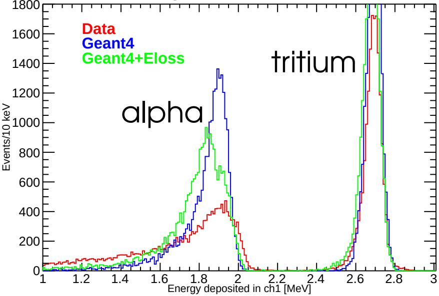




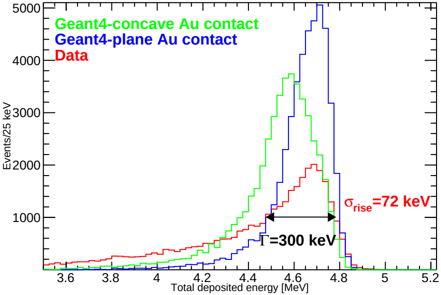
Calibration with Thermal Neutrons

- t-peak resolution was 35 keV (RMS), where 24 keV due to electronics ($NF \simeq 0.8$ dB, $f_H < \frac{1}{2\pi 60ns} \simeq 3MHz$, $V_{rms} \simeq 0.8\ \mu$V, $E/Q \simeq 81$ keV/fC, expected 20 keV),
- α-peak exhibits excessive energy loss tail at l.h.s.,
- total energy peak rise resolution (no eloss): 72 keV,
- total energy peak full width: 300 keV,
- efficiency at $E_n = 0$ was 2.3×10^{-5} cps/nv.

Single Diamond

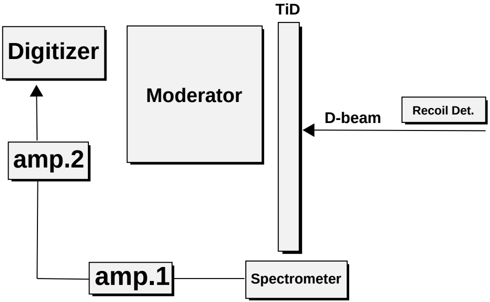


Sum of Two Diamonds



Experiment at FNG (ENEA, Frascati)

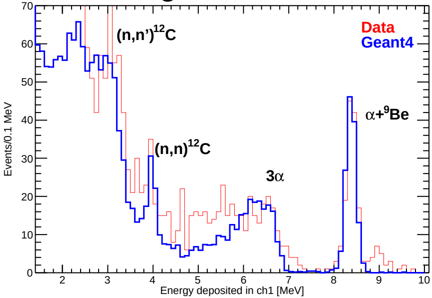
- FNG operated in DD-mode (264 keV D on TiD target),
- spectrometer was installed at 90^o (2.58 MeV n),
- spectrometer located at 2.8 cm distance,
- seen neutron flux was 2.4×10^6 n/cm^{2}s,
- plastic moderator for on-line calibrations,
- 3 runs in OR with 6×10^3 events each recorded,
- 5 runs in AND with 6×10^2 (one 6×10^3) events.



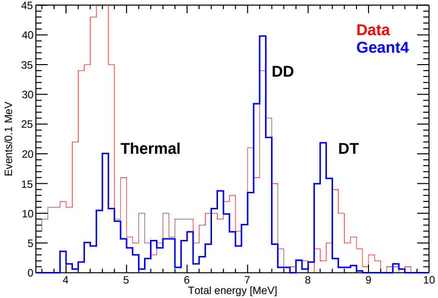
Calibration with 2.5 MeV Neutrons

- thermal n produced t-peak resolution was 34 keV (RMS) compatible with TRIGA measurement,
- α+^{9}Be-peak resolution was 100 keV (RMS) due to beam energy spread of 90 keV (MCNP),
- DD-peak (2.5 MeV n) resolution was 100 keV (RMS),
- efficiency at $E_n = 2.5$ MeV was 4.5×10^{-9} cps/nv,
- large DT contamination is observed (0.25%).

Single Diamond

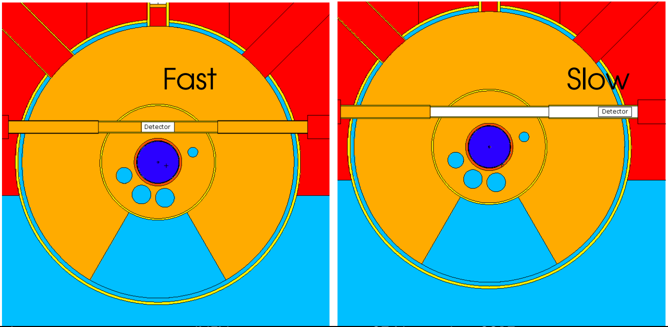


Sum of Two Diamonds



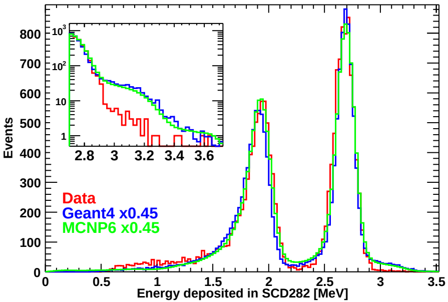
Irradiation Points at TAPIRO (ENEA, Casaccia)

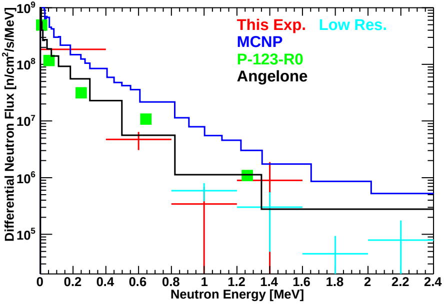
- TAPIRO has 12 cm diameter 93.5% enriched ^{235}U core, 5 kW power/10^{12} n/cm^{2}s, Copper reflector. Tangential channel: +5 cm from median plane, 10.6 cm distance from core center, 3 cm diameter near core.
- Two irradiation points: for fast and slow neutrons.
- Fast position: 5 cm in reflector.
- Slow position: at the edge of reflector (40 cm).



Neutron Spectrum in Slow Position

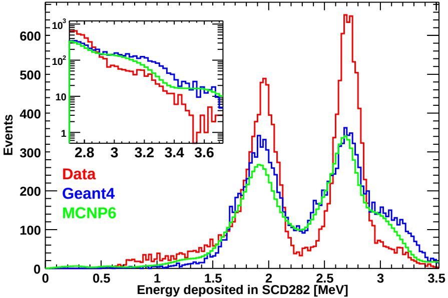
- 20m runtime at 12 W reactor power, trigger rate 13 Hz.
- Total measured flux $\sim$ 50% of expected from MCNP simulations, normalized (in different point) to activation foil measurement at 3.5 kW reactor power,
- measured spectrum was $\sim$ 40% softer than expected.
- Discrepancies can be related to low power of reactor (w.r.t. nominal 5 kW) and large spacial extrapolations from reactor calibration point.

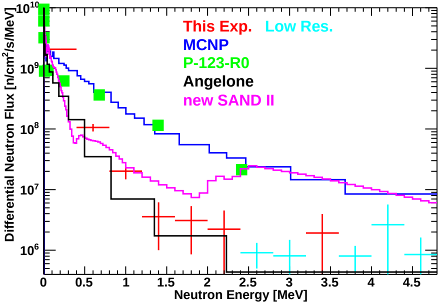




Neutron Spectrum in Fast Position

- 6m runtime at 5 W reactor power, trigger rate 44 Hz.
- Total measured flux $\sim$ 90% of expected from MCNP simulations, normalized (in different point) to activation foil measurement at 3.5 kW reactor power,
- measured spectrum was $\sim$ 60% softer than expected.
- Low reactor power ought explain the difference.
- Fast reactor neutron spectrum was measured up to 5 MeV in 0.4 MeV bins.





Summary

- development of compact neutron spectrometer for reactor in-core measurements advances,
- new prototype made of two 300 μm thick diamonds with ohmic contacts was assembled and tested,
- measurements showed *good stability and resolution*,
- *no space charge effects* were observed,
- remaining issue: large energy loss by αs will be solved in next prototype.

1. experiment at PTB approved in UE-CHANDA program,
2. interest of CEA for MASURCA reactor characterization,
3. meeting with CAENSys demonstrated interest for TT,
4. additional support from Centro Fermi.

References

1. M.Osipenko et.al, "Neutron spectrometer for fast nuclear reactors", NIM A799, 207 (2015), arXiv:1505.06654,
2. M.Osipenko et.al, "Test of a prototype neutron spectrometer based on diamond detectors in a fast reactor", IEEE.Conf.Pub. 10.1109/ANIMMA.2015.7465605 (2015), arXiv:1505.06314,
3. M.Osipenko et.al, "Upgrade of the compact neutron spectrometer for high flux environments", in press, arXiv:1707.05780,
4. M.Osipenko et.al, "Single Crystal Diamonds for Neutrons", EPJ.Plus 129, 268 (2014),
5. M.Osipenko et.al, "Response of diamond detector sandwich to 14 MeV neutrons", NIM A817, 19 (2016),
6. B.Caiffi et.al, "Proton recoil telescope based on diamond detectors for measurement of fusion neutrons", IEEE Trans.Nucl.Sci.63, 2409 (2016), arXiv:1505.06316,
7. M.Osipenko et.al, "Comparison of Fast Amplifiers for Diamond Detectors", INFN-13-17-GE, airXiv:1310.1000 (2013),
8. B.Caiffi et.al, "Characterization of scCVD diamond detectors with gamma sources", NIM A754, 24 (2014),
9. B.Caiffi et.el, "Analysis of the Response of CVD Diamond Detectors for UV and sX-Ray Plasma Diagnostics Installed at JET", Physics Procedia 62, 79 (2015),