CVD diamonds for fast neutron detection and spectroscopy in high flux environment

INFN-E/RILF

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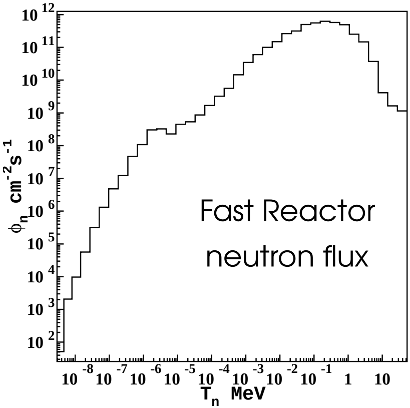
HeRe in Italy ,Frascati, 2013

Motivation

`Goal`: to monitor neutron spectrum inside reactor core.
`Solution`: single crystal CVD diamond detectors.



`Advantages`:

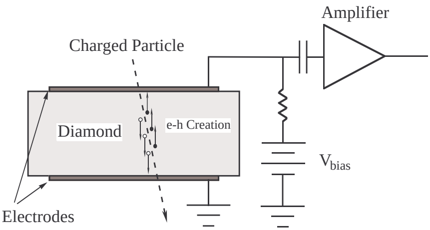
- 100 μm crystal will last for several years at 10^9 n/cm^2/s,
- fast signals good for background rejection,
- compact detectors do not influence reactor kinetics.

`Problems`:

- small signals.

Principle of Detection

- Charged particle crossing diamond creates e-h pairs,
- To collect pairs the bias voltage has to be applied across the diamond,
- Current pulses are generated on electrodes,
- To become measurable the signals have to be amplified.



Crystal Properties

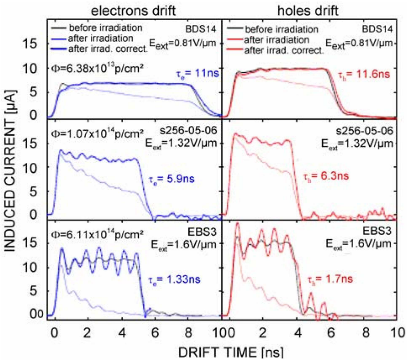
- High bandgap, low capacitance, high carrier mobility $\rightarrow$ fast, low-noise signals

	cvd Diamond	Si	GaN	4H-SiC
Bandgap (eV)	5.47	1.12	3.39	3.27
e-h creation energy (eV)	13	3.6	8-10	8.4
Displacement energy (eV)	43	13-20	10-20	25
Electron mobility (μm^2/V/ns)	200	150	100	80
Hole mobility (μm^2/V/ns)	260	45	20	12
Density (g/cm^3)	3.52	2.33	6.15	3.21
Resistivity (Ωcm)	$> 10^{11}$	2.3×10^5	$10^4 - 10^8$	10^11
Breakdown field (MV/cm)	10	0.3	5	3-5
Dielectric constant	5.7	11.9	9.5	9.7

Signal Formation

- For 1 keV of deposited energy $N_{eh} = 77$ e-h pairs are created;
- Statistical uncertainty on created charge is $\sqrt{F \times N_{eh}}$ (3% for 1 keV), where $F \simeq 0.08$ is diamond Fano factor;
- Charges drift towards electrodes generating current for time t_c:

$$I(t) = \frac{Q(t)}{d} \mu E(x(t))$$



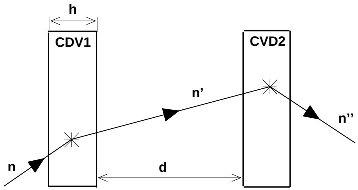
d-thickness; e,h-mobility:

$$\mu = \frac{d^2}{t_c V_{bias}}$$

Time of Flight Technique

Measure the coincidence between two subsequent neutron interactions:

$$T_n = \Delta T_n + \frac{M_n}{2}\left(\frac{d}{c\Delta t}\right)^2$$



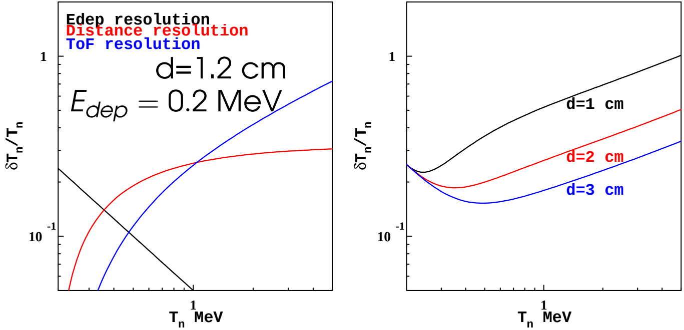
ΔT_n - energy lost in first interaction,
Δt - time interval between two interactions.

Threshold deposited energy is critical:

- minimal accessible neutron energy $T_n^{min} \sim 5E_{thr}$,
- efficiency loss $\epsilon(E_{thr})/\epsilon(E_{thr}=0) \sim (T_n/7E_{thr}-1)^2$.

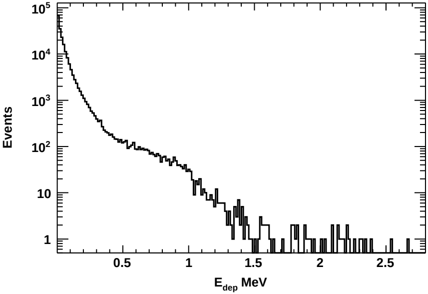
ToF Energy Resolution

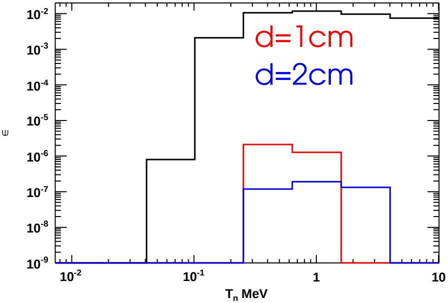
- Assume ToF resolution $\delta_{\Delta t} = 30$ ps at 1 MeV.
- Assume E_{dep} resolution $\delta_{\Delta E} = 50$ keV.
- Requires development of a new, high precision coincidence electronics.



ToF Efficiency

- Geant4 simulations of the detector were performed,
- using ADS neutron flux 10^9 n/cm^2/s and 50 keV detection threshold,
- at ToF distance $d = 2$ cm (1 cm) integrated coincidence rate: 0.6 kHz (2.5 kHz), efficiency $\epsilon^2 A = 5 \times 10^{-6}$ ($\epsilon^2 A = 2 \times 10^{-5}$).





Accidental Coincidences

- Assuming trigger window $\Delta t = 10$ ns:

$$R_{acc} = R^2_{single}\Delta t = 70kHz \tag{1}$$

  28 (d=1 cm) - 125 (d=2 cm) times higher than signal rate.

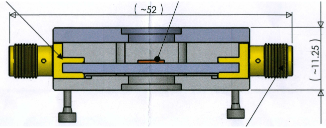
- However, only 0.026 accidental signals appear in an open 10 ns gate.
- General the trend of Signal-to-Noise-Ratio:

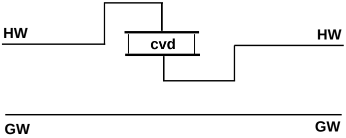
$$SNR = \frac{1}{\pi \phi_n d^2 \Delta t} \tag{2}$$

CVD Diamond Crystals

Diamond Detectors Ltd. SO-274:

- 4.7×4.7 mm^2 surface area and 500 μm thick;
- Atomic impurities: N$<$5 ppb, B$<<$5 ppb (spectroscopic grade),
- Surface scan RMS for side 1: 1.37 nm, side 2: 0.71 nm;
- DLC (1-3 nm)/Pt (50 nm)/Au (100 nm) ohmic contacts, area 22 mm^2, $C_D = 2.2$ pF;
- Brass/aluminum casing with two SMA-F connectors.





Experimental Setup

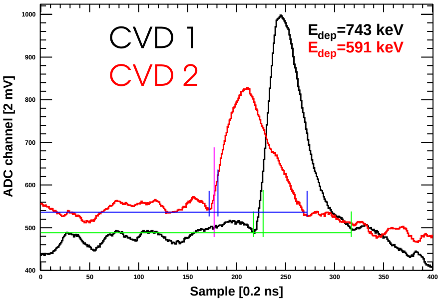
- FNG in D-D mode (2.5 MeV monocromatic neutron beam),
- neutron flux of 10^6 n/cm^2/s,
- two CVD crystals were placed at distance $d = 1.2$ cm,
- signals preamplified by fast transimpedance amplifiers (see R. Cardarelli talk) connected trough 5 m cable to the secondary amplifier P/S 774.
- DAQ: NIM crate (power supplier, secondary amplifier), VME crate (5 Gs/s digitizer, controller/PC).

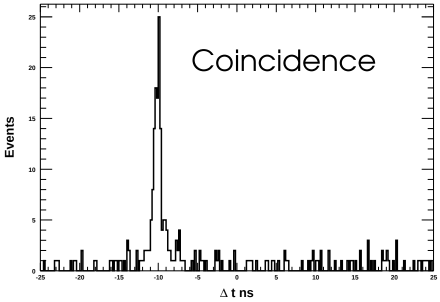
Pictures

Two DDL diamonds attached

Results

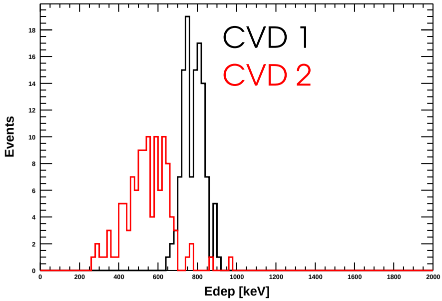
- 120 coincidence events/540 s - expected 0.25 Hz, ✓
- 5% accidentals ($\Delta t = 2$ ns) - as expected, ✓
- ToF is 0.6 ns, with timing resolutions of 0.36 ns ($\delta_{\Delta t} = 250$ ps of two amplifiers at 1 MeV) and 0.1 ns (distance),
- observed peak RMS is 0.4 ns, in agreement with estimates (100% T_n resolution).

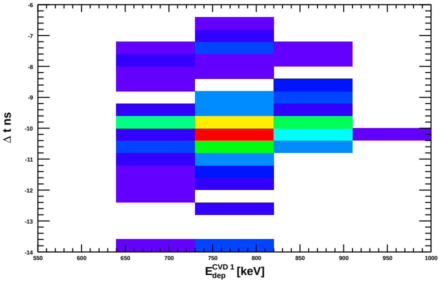




Results cont.

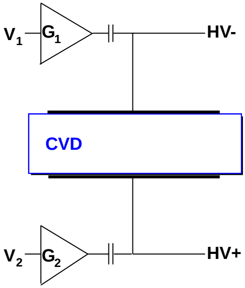
- energy thresholds were set ~ 0.25 MeV,
- deposited energy resolution ~ 50 keV,
- only backscattered n were detected in CVD 1 (threshold for forward n $7\div27$ keV),
- in CVD 2 flat angular distribution, $\theta_n^{CM} > 70^\circ$,
- within covered energy range ToF variation < 10 ps.

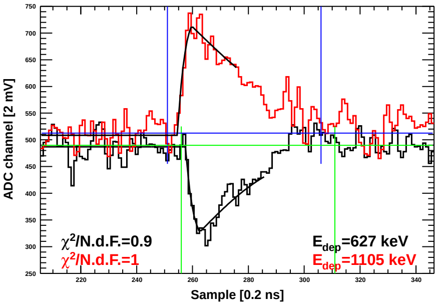




Amplifier Test

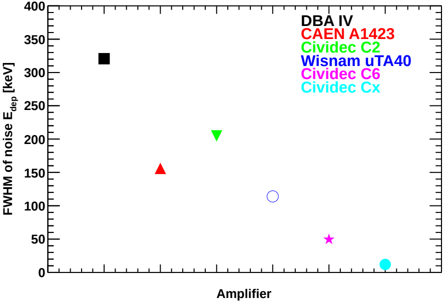
- compared five fast amplifiers: DBA IV, CAEN A1423, Cividec C2, Wisnam μTA40 and Cividec C6,
- ^{241}Am (α, 5 MeV) and ^{90}Sr ($\beta < 2.3$ MeV) sources,
- CVD diamond detector read out independently from two sides,
- 5 Gs/s (2 GHz BW) digitizer recorded the signals.

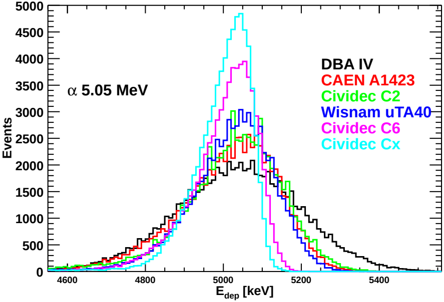




Amplifier Energy Resolution

- measured noise level in terms of energy deposited in diamond,
- obtained peak shape 5 MeV α from ^{241}Am source,
- among fast amplifiers best resolution Cividec C6 (100 MHz BW).

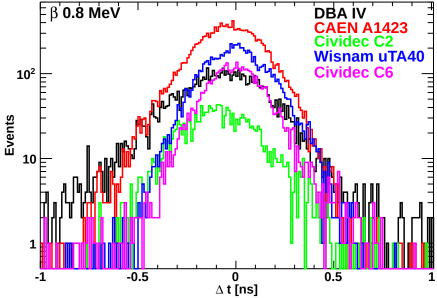


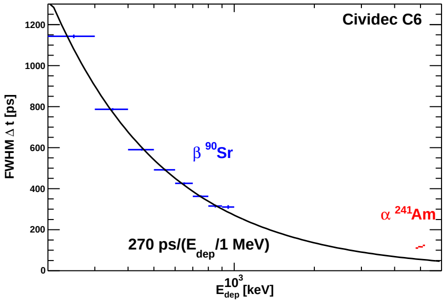


Amplifier Timing Resolution

- coincidence between two electrodes,
- ^{241}Am (α, 5 MeV) and ^{90}Sr ($\beta < 2.3$ MeV) sources,
- Cividec C6 has best timing resolution,
- energy dependence of timing resolution agrees with

$$\sigma_t = \frac{t_{rise}}{S/N}$$





Summary

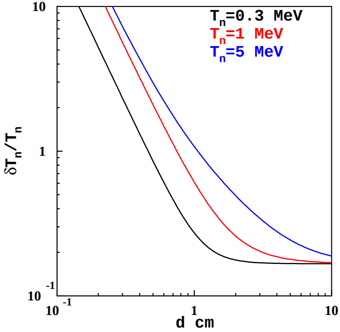
- scCVD diamonds were proposed for ToF neutron spectrometer ($10^5 < \phi_n < 10^9$ n/cm^2/s),
- test measurement at FNG demonstrated feasibility of technique,
- number of commercial amplifiers were tested,
- noise level of existing amplifiers has to be improved by a factor of 10.

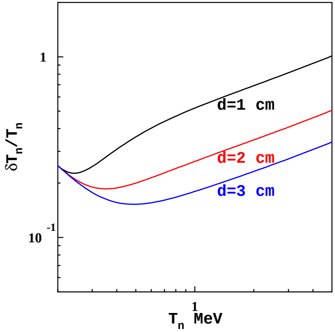
- Future:
  - develop better signal amplifier,
  - optimize detector geometry,
  - test at FNG and research reactors.

Backup Slides

Resolution vs. Distance

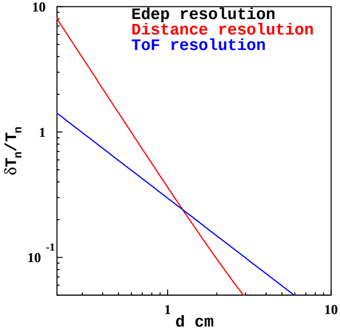
- Two 500 μm crystals at distance d;
- Assume ToF resolution $\delta_{\Delta t} = 0.2$ ns;
- Assume E_{dep} resolution $\delta_{\Delta E} = 50$ keV.

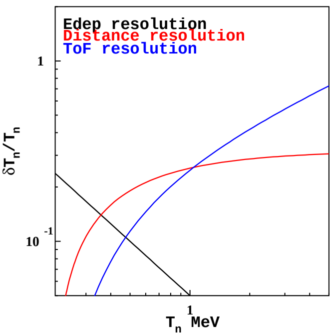




Resolution Contributions

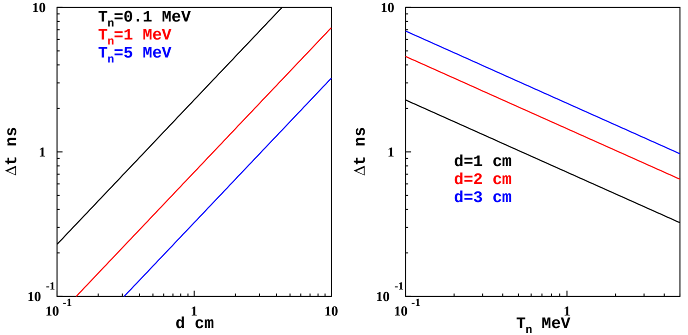
- For $d > 2$ cm and $T_n > 0.4$ MeV ToF resolution dominates;
- Develop high precision coincidence technique;
- 25 ps resolution has been achieved with diamonds.





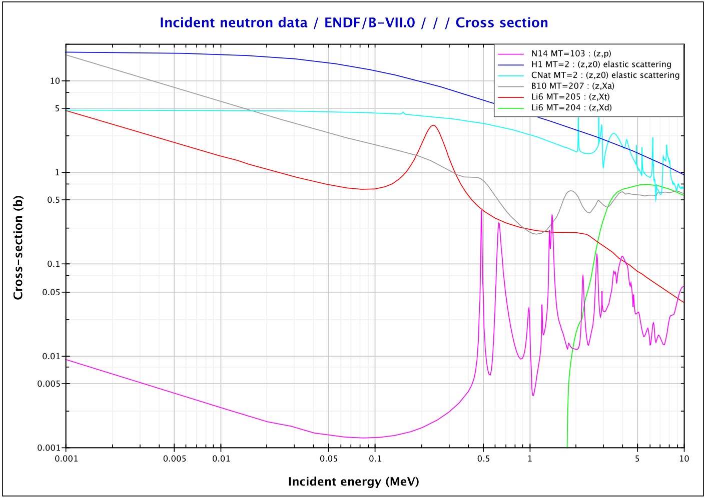
ToF Resolution Cont.

- In region of interest ToF vary from 0.5 to 7 ns.



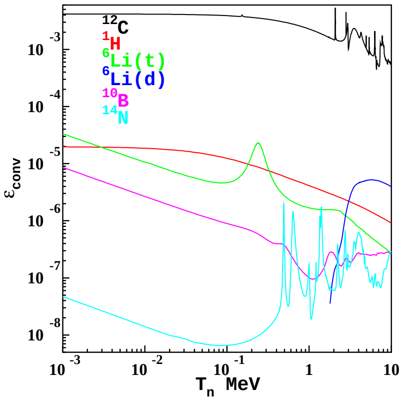
Conversion Cross Sections

Hydrogen and Carbon have highest cross sections.



Conversion Efficiency

Assuming 10% of range convertor thickness.



- Deposited energy threshold not considered,
- Acceptance of diamonds seen from converter not included,
- 10% of range probably gives poor resolution.

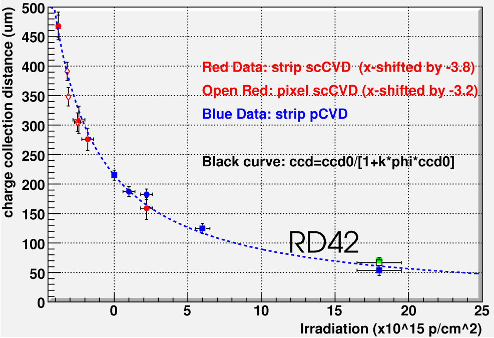
Other Active Detectors

In fluxes <10^{12} n/cm^2/s Diamond detector can substitute Fission Chamber as active monitor.

	Fission Chamber	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
Size	4×10 mm^2	2×2 mm^2
Converter	U,Th,Pu	H, Li, B
Efficiency at 0.5 MeV	1.1 barn	0.4 barn (^{6}Li)
Signal Size	200 fC	60 fC (^{6}Li)
Spectroscopy	unfolding	direct (^{6}Li)
Energy Range	entire	<7 MeV (^{6}Li)

Robustness

Diamonds are `radiation hard`.

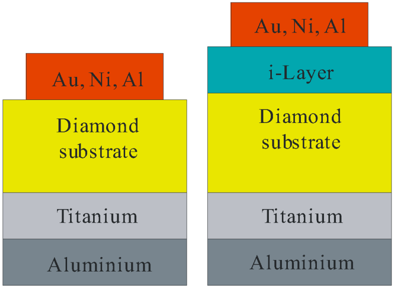


- `Neutrons`: up to 4×10^{15} of 14.8 MeV n/cm^2 $\sim$ 0.25 MGy,
- `Photons`: up to 10 MGy,
- `MIPs` (24 GeV p): up to 4×10^{15} p/cm^2 $\sim$ 1.25 MGy,

Signal Collection

- Electrode contacts can be ohmic or Schottcky (rectifying);
- Ohmic contacts: charge can flow through (Ti or Cr which form carbide at 500° annealing followed by Pt and Au);
- Schottcky (rectifying) contacts: charge remain in detector bulk (e.g. Al).

ϕ_s: C 4.8-5.8 eV (p-type);
ϕ_m: Al 4.1 eV, Ti 4.3 eV, Cr 4.5 eV, Au 5.1 eV, Pt 5.7 eV;
p-type ohmic: $\phi_s < \phi_m$



(p) Sample (i-p) Sample

Signal Description

Space charge (τ^{sc}) and trapping $\tau_{e,h}$ lifetimes ($\sim$ 40 ns):

$$I_{e,h}(t) \sim e^{\pm t/\tau^{sc}_{e,h} - t/\tau_{e,h}}$$

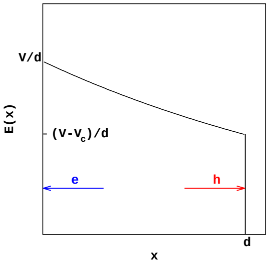
Drift velocity:

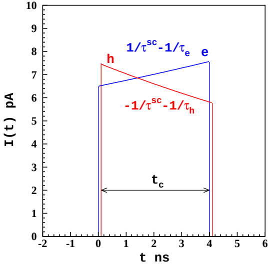
$$v_{drift} = \frac{d}{t_c}$$

Charge collection distance:

$$\frac{ccd}{d} = \frac{Q}{Q_0}$$

$$Q = \int I(t)dt \simeq 1 - \frac{d}{2\tau_{e,h} v_{drift}}$$





For Further Reading I

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