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. $^{238}\text{U}$),
2. activation foils producing relatively long lived isotopes/levels, e.g. by (n,p) reaction.

- counting rate/activity of isotope $i$:
  \[ A_i \approx \int_{E_{i}^{\text{th}}}^{\infty} \Sigma(E_n)\phi_n(E_n)\,dE_n , \]

- system of $N$ integral equations with different threshold energies $E_{i}^{\text{th}}$ 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:

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

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. $(n,d)^{6}\text{Li}$ reaction contributes for $E_n > 3_{\text{kin.}} + 4_{\text{th.}}$ MeV,
5. $(n,\alpha)^{12}\text{C}$ reaction dominates at $E_n > 6_{\text{kin.}} + 4_{\text{th.}}$ MeV.

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Converter

Detector1

Detector2

CVD intrinsic

$^{6}\text{LiF}$ converter

CVD intrinsic

Output 1

GND

Output 2
Diamond Detector vs. Gas Proportional Counter

Gas filled detectors are slow, bulky, but harder:

<table>
<thead>
<tr>
<th></th>
<th>Proportional Counter</th>
<th>Diamond Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Mobility</td>
<td>0.3-0.4 cm²/V/s</td>
<td>2000 cm²/V/s</td>
</tr>
<tr>
<td>Charge Collection time</td>
<td>5-7 µs</td>
<td>2-10 ns</td>
</tr>
<tr>
<td>Counting Rate</td>
<td>20 kHz</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Converter</td>
<td>H, ³He, ¹⁰B</td>
<td>H, ⁶Li, ¹⁰B</td>
</tr>
<tr>
<td>Energy loss</td>
<td>0.35 MeV/cm/bar</td>
<td>392 MeV/cm</td>
</tr>
<tr>
<td>Range at 7 MeV</td>
<td>60 cm/bar</td>
<td>150 µm</td>
</tr>
<tr>
<td>Size</td>
<td>10 cm</td>
<td>2 mm</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>very high</td>
<td>&lt; 10¹⁶ n/cm²</td>
</tr>
</tbody>
</table>

Comparison with Silicon detector:
- factor ×4-10 lower radiation damage (σ_C(n,n') × Z_C²ρ_C),
- no intrinsic noise at high temperature (E_g = 5.5 eV).
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 $3 \times 10^{16}$ 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.

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

arxiv.org/1510.05415
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 $10^8 \, \Omega \text{cm}$,
- 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.

\[ W_{14} \sim 10^{-14} \text{ CVD} \]
\[ C_{\text{decouple}} \sim 1 \text{ nF} \]
\[ C_{\text{CVD}} \sim 1 \text{ pF} \]
\[ R_{\text{CVD}} \sim 10^{14} \Omega \]
\[ \text{Diamond detector} \]
\[ \text{HV} \sim 300 \text{ V} \]

\[ \begin{array}{c|c}
\text{t [ns]} & \text{V_{out} [mV]} \\
0 & 0 \\
5 & 200 \\
10 & 400 \\
15 & 600 \\
20 & 800 \\
25 & 1000 \\
30 & 1200 \\
\end{array} \]

\( \alpha 5 \text{ MeV} \times 1000 \)
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 $6 \times 10^4$ events each recorded.

\[ \chi^2 / \text{ndf} \quad 79.55 / 39 \]
\[ p_0 \quad -16.92 \pm 4.718 \]
\[ p_1 \quad 72.31 \pm 0.8136 \]
Introduction Detector Calibrations Fast Reactor Conclusion

Calibration with Thermal Neutrons

- t-peak resolution was 35 keV (RMS), where 24 keV due to electronics ($NF \approx 0.8$ dB, $f_H < \frac{1}{2\pi 60\text{ns}} \approx 3\text{MHz}$, $V_{rms} \approx 0.8 \mu\text{V}$, $E/Q \approx 81 \text{ keV}/\text{fC}$, expected 20 keV),
- $\alpha$-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 $2.3 \times 10^{-5}$ cps/nv.

Single Diamond

<table>
<thead>
<tr>
<th>Energy deposited in ch1 [MeV]</th>
<th>Events/10 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td></td>
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<tr>
<td>1.8</td>
<td></td>
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<tr>
<td>2</td>
<td></td>
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<tr>
<td>2.2</td>
<td></td>
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<tr>
<td>2.4</td>
<td></td>
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<td>2.6</td>
<td></td>
</tr>
<tr>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
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</tbody>
</table>

Tritium

Data
Geant4
Geant4+Eloss

Sum of Two Diamonds

<table>
<thead>
<tr>
<th>Total deposited energy [MeV]</th>
<th>Events/25 keV</th>
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<tr>
<td>3.6</td>
<td></td>
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<tr>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Geant4-concave Au contact
Geant4-plane Au contact
Data

$\sigma_{\text{rise}} = 72$ keV
$\sigma = 300$ keV
Experiment at FNG (NEA, Frascati)

- FNG operated in DD-mode (264 keV D on TiD target),
- spectrometer was installed at 90° (2.58 MeV n),
- spectrometer located at 2.8 cm distance,
- seen neutron flux was $2.4 \times 10^6$ n/cm$^2$/s,
- plastic moderator for on-line calibrations,
- 3 runs in OR with $6 \times 10^3$ events each recorded,
- 5 runs in AND with $6 \times 10^2$ (one $6 \times 10^3$) events.
Calibration with 2.5 MeV Neutrons

- thermal n produced t-peak resolution was 34 keV (RMS) compatible with TRIGA measurement,
- $\alpha^+{^9}\text{Be}$-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 $4.5 \times 10^{-9}$ 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.

![Graph of neutron spectrum](attachment:image.png)
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.

![Graph of neutron spectrum](image-url)

**Energy deposited in SCD282 [MeV]**

<table>
<thead>
<tr>
<th>Events</th>
<th>Data</th>
<th>Geant4</th>
<th>MCNP6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>100</td>
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<tr>
<td>1</td>
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<td>500</td>
<td>500</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>600</td>
<td>600</td>
</tr>
</tbody>
</table>

**Differential Neutron Flux [n/cm$^2$/s/MeV]**

<table>
<thead>
<tr>
<th>Neutron Energy [MeV]</th>
<th>This Exp.</th>
<th>Low Res.</th>
<th>MCNP</th>
<th>P-123-R0</th>
<th>Angelone</th>
<th>new SAND II</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>10$^9$</td>
<td>10$^8$</td>
<td>10$^7$</td>
<td>10$^6$</td>
<td>10$^5$</td>
<td>10$^4$</td>
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<tr>
<td>0.5</td>
<td>10$^9$</td>
<td>10$^8$</td>
<td>10$^7$</td>
<td>10$^6$</td>
<td>10$^5$</td>
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<td>10$^7$</td>
<td>10$^6$</td>
<td>10$^5$</td>
<td>10$^4$</td>
</tr>
</tbody>
</table>
Summary

- development of compact neutron spectrometer for reactor in-core measurements advances,
- new prototype made of two 300 $\mu$m 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 $\alpha$s 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 CAENSyss demonstrated interest for TT,
4. additional support from Centro Fermi.
References

8. B. Caiffi et al., “Characterization of scCVD diamond detectors with gamma sources”, NIM A754, 24 (2014),