Analysis of CVD diamonds for neutron detection on the OMEGA laser

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I. Abstract

Neutron energy deposition in chemical vapor deposition (CVD) diamond detectors was quantified. Diamond detectors have significant advantages over scintillator systems for neutron detection since they express faster response times, have enhanced energy resolution, and can be operated at room temperature. Data were obtained for four detectors used on the OMEGA laser. A neutron detection model was developed to quantify the energy deposited per neutron interaction using measured detector sensitivities. The average energy deposited per neutron interaction was 27 to 44 keV for 14-MeV neutrons and 4.8 keV for 2.5-MeV neutrons. Using the known electron mobility in diamond and signal rise times, the effective thicknesses of the detectors were calculated. T his work establishes an energy deposition model that will aid in the development of future CVD diamond detectors for use in fusion reaction diagnostics.

II. Introduction

Harnessing the energy from fusion reactions remains a tantalizing opportunity for creating a source of clean renewable energy. The field of fusion research has advanced through a greater understanding of high-energy laser-matter interactions. At the OMEGA facility, 60 laser beams provide a total of 30 kJ to a small, spherical target containing deuterium (D) and tritium (T) isotopes in order to create fusion reactions during an implosion. While the ultimate goal of a sustainable fusion reaction has not yet been reached, increased efforts are currently underway to improve the quality, stability and uniformity of implosions. The OMEGA laser beams deliver enough energy to overcome the electromagnetic force of repulsion that occurs between positively charged deuterium and tritium. As a result, two major reactions occur during an implosion at OMEGA:

1. $D+D \rightarrow {}^{3}He(0.82MeV)+n(2.45MeV)$ $\quad Q = 3.27MeV$

2. $D+T \rightarrow {}^{4}He(3.56MeV)+n(14.03MeV)$ $\quad Q = 17.59MeV$[1]

These reactions, the fundamental process of energy generation at OMEGA, are illustrated in **Fig 1**.

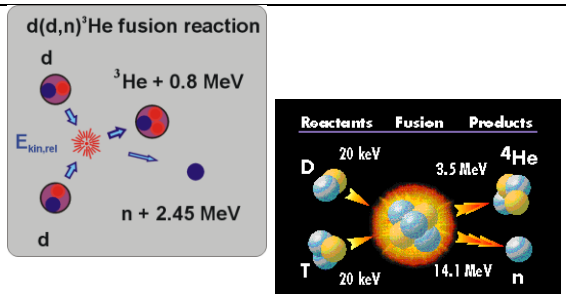

Figure 1: Diagram of the DD and DT reactions that occur at OMEGA. The primary interest of CVD diamond detection systems is the emitted neutrons from each reaction. [1]

In both cases, most of the reaction energy (Q) is stored in an emitted neutron. Thus, in the hopes of improving the energy output and gain of fusion reactions it is critically important to understand the nature of these emitted neutrons. Furthermore, a thorough analysis of the resulting neutron spectra lends insight into critical aspects of the implosion itself such as the fuel ion temperature, density, and the time of maximum compression. A thorough neutron diagnostics suite is essential for the advancement of fusion energy research.

A wide variety of neutron diagnostics systems are used at OMEGA to analyze and detect the emitted neutron spectra emitted from an implosion. Most detection schemes involve the use of plastic or liquid scintillators, which measure the light output created when neutrons interact with the detector. Although traditional scintillators provide critical information about the emitted neutrons, they are hindered by some problematic flaws inherent to their detection mechanism and overall design. First, scintillators have a tendency to age over time, leading a change in their detection properties over time and forcing researchers to adjust and recalibrate. Furthermore, scintillators have a long time response, which prevents them from being utilized effectively at short distances from the target chamber center (TCC). In high-radiation magnetic fusion environments, highly energetic neutrons and other forms of radiation can cause damage to scintillators and reduce their overall effectiveness. While scintillators will always be a staple of neutron diagnostics, other neutron detection mechanisms must also be considered. A novel detection system that utilizes synthetic diamonds is currently in use in the OMEGA facility.

Chemical vapor deposition (CVD) diamond detectors[2-5] utilize semiconductor properties to detect neutrons. Incident neutrons interact with stationary carbon atoms through collisions to create charged electron-hole pairs. As seen in **Fig 2,** under an applied E-field, the pairs migrate towards the electrodes and create an electrical signal.

Diamond possesses significant and promising advantages over scintillators due to its inherently wide bandgap of 5.5 eV, which reduces the amount of noise generated in the output signal. Additionally, the high density and radiation hardness of diamond provides great tolerance to the radiation-intensive environments that can be found in some fusion environments. The short lifetime of charge carriers in diamonds allows these detectors to have a fast time response, leading to accurate signal outputs at very short distances from TCC. Chemical vapor deposition (CVD) is an emerging technique used to emulate the attractive qualities that can be found in naturally occurring diamond. Since natural diamond is rare and expensive, CVD techniques allow for the artificial growth of diamond crystals in a high-pressure, high-temperature environment. The growth and deposition process is both precise and highly controlled to allow for the optimization of crystal structure and to minimize defects such as bubbles and irregularities that might impede charge flow through the diamond.

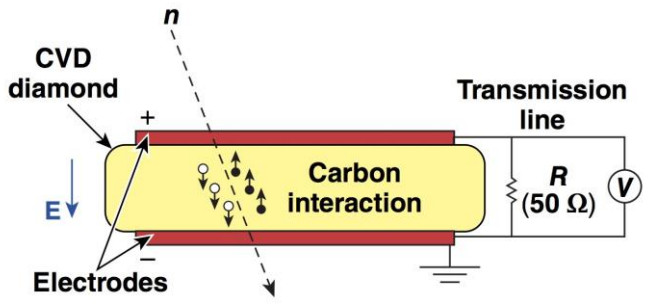

Figure 2: Schematic of electron hole-pair generation in a CVD diamond detector lattice.

Extensive research has been conducted over the last three decades regarding the use of CVD diamonds for particle detection in fusion environments. While significant progress has been made into improving the overall quality and design of these detectors, the sensitivity difference between 2.45 MeV neutrons and 14 MeV neutrons has not been fully solved. Through the analysis of signal outputs as well as the physical properties of these detectors, this study quantifies the energy deposition that occurs in these diamonds from neutron interactions. In the hopes of creating the next generation of highly sensitive and highly dynamic detectors, a thorough understanding of energy deposition and signal generation from various neutron sources is essential.

This study creates and tests a model that quantifies the energy deposition that occurs in diamond detectors from neutron interactions. Using measured detector sensitivities, calculated neutron interactions, and the solid angle of the detector the energy deposition per neutron interaction was calculated using this model. Additionally, using signal rise times, the effective thickness of the detectors was calculated. This analysis represents a unique investigation into the energy deposition interaction that occurs when emitted neutrons enter the detection lattice.

III. Signal generation in CVD diamond detectors

Diamond detectors rely on a neutron energy conversion process in order to generate a signal. Emitted neutrons during an implosion travel through the OMEGA bay and impact the diamond surface of the detector. Through particle collisions, highly energetic neutrons interact with stationary carbon nuclei through multiple reaction channels to generate charged particles. The reaction channels of primary interest are shown in **Table 1**, taken from Ref.6:

Table 1: Reaction channels between incident neutrons and carbon lattice from Ref. 6.

Reaction	Threshold (MeV)
$^{12}C(n,\gamma)\ ^{13}C$	0
$^{12}C(n,\alpha)^{9}Be$	6.18
$^{12}C(n,n'2\alpha)^{4}He$	7.88
$^{12}C(n,n'\alpha)^{8}Be$	7.98
$^{12}C(n,2\alpha)^{5}He$	8.85
$^{12}C(n,p)^{12}Be$	13.64

Of these reactions, the ^{12}C (n, α) ^{9}Be reaction is critical as it contributes the greatest towards signal generation. The high threshold of 6.18 MeV allows for the reduction of signal noise from other particle emissions that occur during a target implosion. In the diamond lattice, the resulting charged particles—namely alpha and beryllium—generate electron-hole pairs through the excitation of electrons from the valence band to the conductance band. This continuous charge migration of electrons traveling to the positive electrode and their corresponding "holes" traveling to the negative electrode creates a current, which can be measured by a voltmeter following appropriate amplification and noise reduction. The duration of charge carrier generation is directly linked to the duration of incident neutron collisions; a peak in the voltage signal is directly correlated to a pulse of neutrons.

Signal generation is highly dependent on the intrinsic properties of the diamond lattice itself since defects or irregularities can impede the natural flow of electrons towards the positive electrode. Thus,

the manufacturing process of each synthetic diamond must be considered in order to improve detection accuracy and detector sensitivity.

Currently, there are three active CVD diamond detectors installed on OMEGA. The first is installed 5.8 m from TCC, the second is 15.9 m from TCC and the third is 5.0m from TCC. This work focuses on the two CVD diamond detectors that are part of a new 3-axis detector system on OMEGA. These are the 5.8 m and 15.9 m detectors which are located along the same line-of-sight. The voltage signals from the detectors undergo processing through connected electronics, which typically consist of an amplifier and a voltmeter. Using MATLAB routines, the data from the voltmeter can be used to combine the signal outputs from the different detectors as a function of time, as shown in **Fig.3**. The fixed CVD detector positions as well as the predictability of neutron production and flight leads to relatively consistent signal shapes over multiple shots and various experiments.

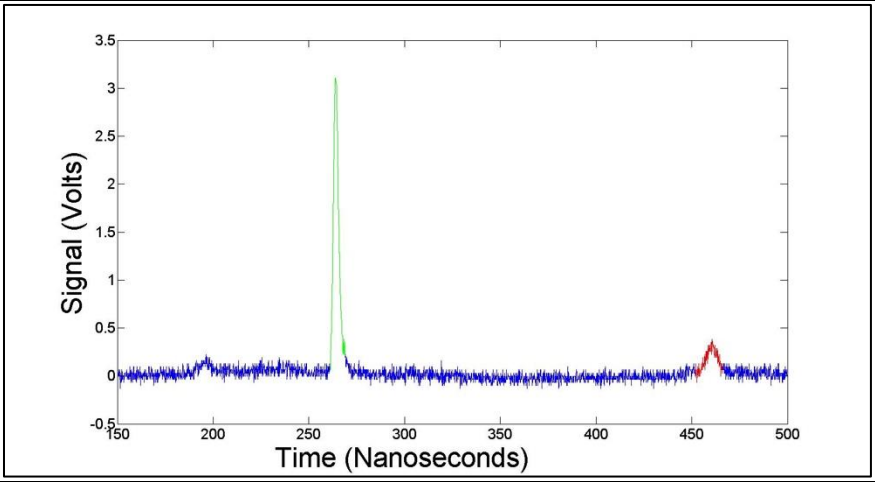

Figure 3: Signal output of a DT reaction as viewed in MATLAB programming software. The green peak indicates the signal generated at the 5.8 m CVD and the red peak indicates the signal generated at the 15.9-m CVD. The rise time, amplitude and full width at half maximum of this signal contain information regarding the neutrons emitted from the implosion.

The two distinctive peaks in **Fig 3** indicate the arrival of neutrons at each of the detectors. The first peak is the signal output from the closer detector at 5.845 m from TCC. It is important to note that the peak from the first detector is several times greater than the peak from the second detector (red). Furthermore, significant noise can be visualized in the peak signal output from the far detector, which can be attributed to various factors including neutron scattering background from the surrounding structures and a significantly smaller amount of incident neutrons at that distance. The small blue peak seen at around 170 ns is generated from gamma radiation that was created when the neutrons collided with the inner surface of the target chamber. The integral of the peak signal is used to calculate the sensitivity and energy deposition in these detectors, as shown in the following sections. Multiple voltage signals from two different campaigns on OMEGA were used to characterize the performance of four CVD diamond detectors.

IV. Energy deposition model

A phenomenological model was created to estimate the energy deposited per neutron interaction in a CVD detector. Estimating this energy is important as it provides insight into the capacity of CVD diamond detectors to withstand high energy fluxes and is relevant to understanding energy saturation in these detectors. This model incorporates detector location, reaction cross-section, and measured signal data to generate a value.

First, the number of neutron interactions (N_{int}) within the diamond detector lattice is calculated.

$$N_{int} = N_{inc}\sigma t n_c \quad (1)$$

where N_{inc} indicates the number of incident neutrons, σ is the total cross section for neutron-carbon interactions, t is the thickness of the detector and n_c is the number density of carbon atoms. The

likelihood of interaction is thus directly dependent on the cross section for the reaction, which varies based on the incident neutron energy.

The number of incident neutrons is calculated as follows:

$$N_{inc} = N_y * \frac{\Omega_{det}}{4\pi} \quad (2)$$

where N_y is the total neutron yield for the implosion, and Ω_{det} is the detector solid angle. The number of incident neutrons differs from the number of neutron interactions because only a fraction of the incident neutrons will interact with carbon nuclei. Next, the number of electron-hole pairs (N_{eh}) generated based on signal data is calculated:

$$N_{eh} = \frac{\int V dt}{2eR} \quad (3)$$

where *e* is the electron charge, *R* is the resistance of the detection system, and $\int V dt$ is the integral of the voltage signal over the peak measured by the CVD diamond detector.

Using the number of electron hole pairs generated and the number of interactions within the detector, the average energy deposited per neutron interaction is calculated:

$$E_{dep} = E_0 * \frac{N_{eh}}{N_{int}} \quad (4)$$

where E_0 is the energy needed to create an electron-hole pair in diamond which is 13.2 eV. This model was then applied to four CVD diamond detectors that have been employed in different OMEGA experiments.

V. Setup of CVD diamond detectors

This study analyzes data sets obtained from four CVD diamond detectors in OMEGA, shown in **Fig 4.** A 2005 campaign utilized a CVD diamond detector setup that was situated 0.5 m from TCC and used to measure the bang-time for reactions. This setup consisted of high-yield neutron bang time detectors (HYNBT) that were used for detection of both DD and DT neutron reaction emissions. The two data sets from that campaign used in this study are referred to as HYNBT DT and HYNBT DD data.

As previously discussed, two CVD detectors are currently installed in OMEGA, at 5.845 m and 15.851 m from TCC. These detectors consist of two individual polycrystalline wafers and are located along the P2-P11 axis. Amongst the wide range of neutron diagnostic systems installed on OMEGA, these two CVD diamonds provide the unique ability to calculate the transit time between the two detectors. This transit time over the 10 m between the first detector (5.8-m CVD) and the second detector (15.9-m CVD) can provide information on the motion of the center of the mass of the neutron emitting region.

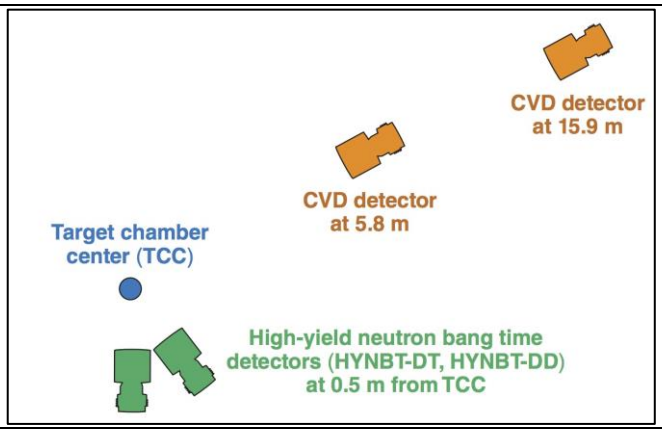

Figure 4: Locations of HYNBT DT, HYNBT DD, 5.8-m CVD and 15.9-m CVD detectors in the OMEGA facility with respect to the target chamber center.

VI. Analyzing detector sensitivity and signal linearity

The first step in understanding the performance of these CVD diamond detector setups was analyzing the relationship between the incident neutrons calculated using **Equation 2** and the signal amplitude obtained as the integral of the voltage signal over the peak. This is shown in **Fig 5** for the four detectors. Linearity of signal output is indicative of detector performance and shows that the detectors have been successfully calibrated to the OMEGA environment.

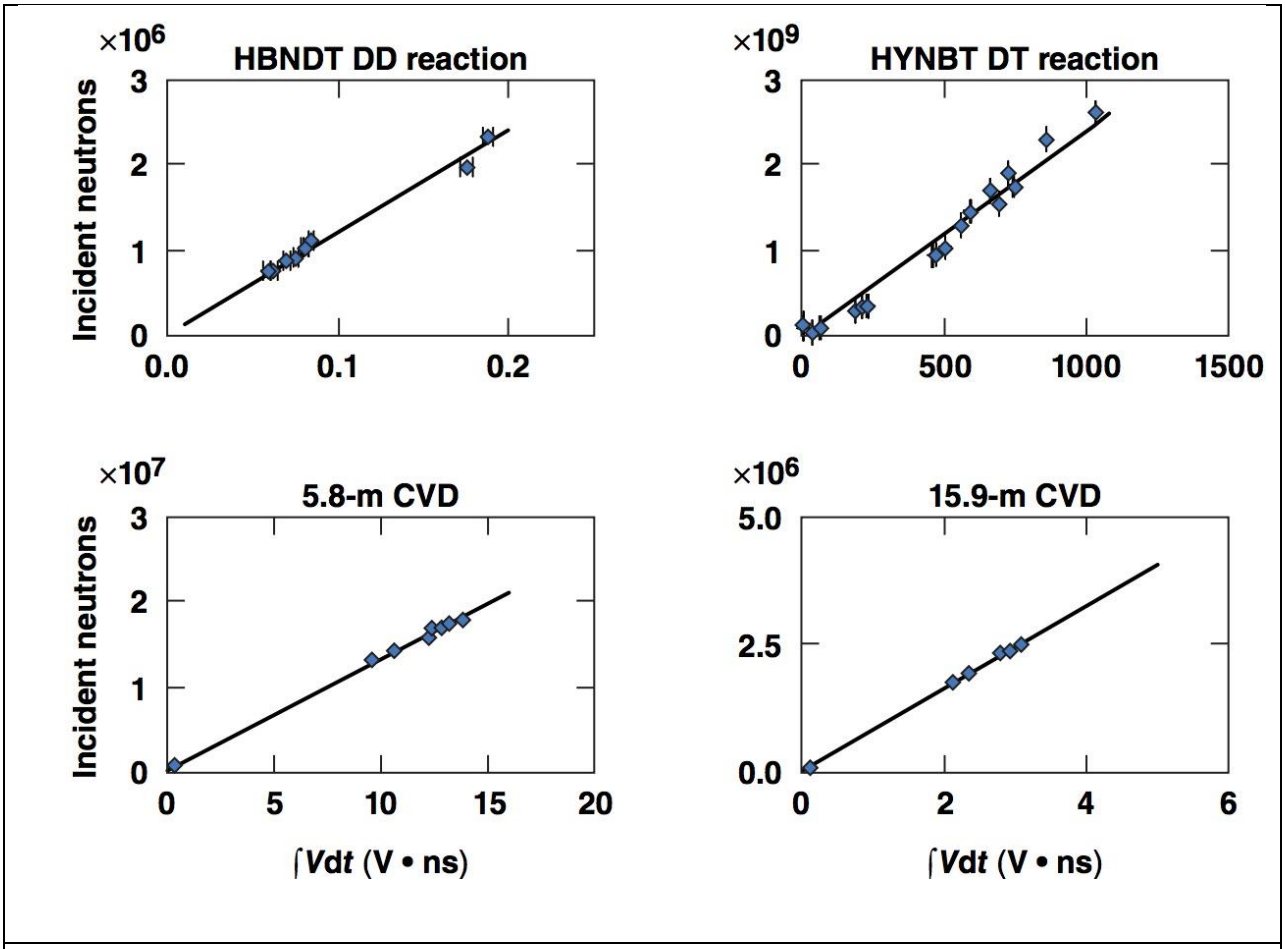

Figure 5: Incident neutron and signal integral plot for the four detectors. Strong signal linearity suggests successful calibration and optimal performance of the detectors.

Further information can be derived from these plots by determining a quantity known as sensitivity. The sensitivity of the detectors (α) in V*ns/neutron is calculated as the signal in volt*ns generated by one incident neutron:

$$\alpha = \frac{\int V dt}{N_{inc}} \quad (5)$$

The sensitivities of the four data sets are shown in **Fig 6.**

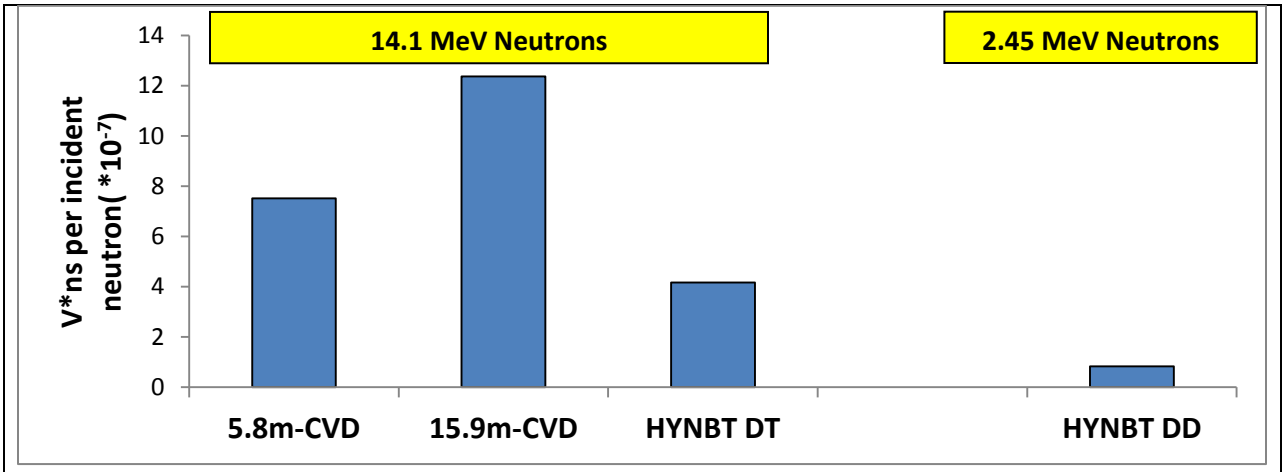

Figure 6: Sensitivity of the four data sets. Sensitivity represents the signal generated in the detector per incident neutron. The data indicates great variability in sensitivity.

Detectors that generate a greater signal per single incident neutron exhibit greater sensitivity. Consequently, **Fig. 6** indicates that the 15.9-m CVD diamond detector exhibits the greatest sensitivity while the HYNBT detector has the lowest sensitivity. When comparing the HYNBT DT data to the HYNBT DD data, the results indicate that the detector has higher sensitivity for 14 MeV neutrons. In addition, as evidenced by **Fig. 6** there is great variation in sensitivity between the four detectors. The variability in

sensitivity could stem from a variety of factors. The fabrication of the detector can affect sensitivity by altering physical properties that affect charge flow such as mosaic structure, unintended dopants, dopant concentration, and crystalline size. These features impact the electron flow within the lattice in different ways, creating differences in signal amplitude and detection capabilities. Additionally, sensitivity scales with thickness in that thicker detectors will exhibit greater sensitivity. Other causes for variation in sensitivity are currently undetermined and merit further exploration. The great variation in sensitivity found in the OMEGA detectors indicates that a more uniform synthesis process will be required in future CVD diamond neutron detection setups. Furthermore, this data indicates that it is critical to consider the specific synthesis process of each CVD diamond wafer when analyzing signal data from these detectors.

VII. Energy deposition in detectors

The central component of this study is the creation and application of a model that utilizes detector data to quantify neutron energy deposition. Quantifying deposited energy for each neutron interaction is important for providing insight into the conditions in which CVD diamond detectors must operate. Furthermore, this study represents a novel analysis, as there are few response models for CVD diamond detectors that explore energy deposition for neutron interactions. The general model developed in **Section IV** was applied to data obtained from the four datasets that were analyzed in pervious sections. The resulting values for energy deposition determined by **Equation 4** are given in **Fig. 7.**

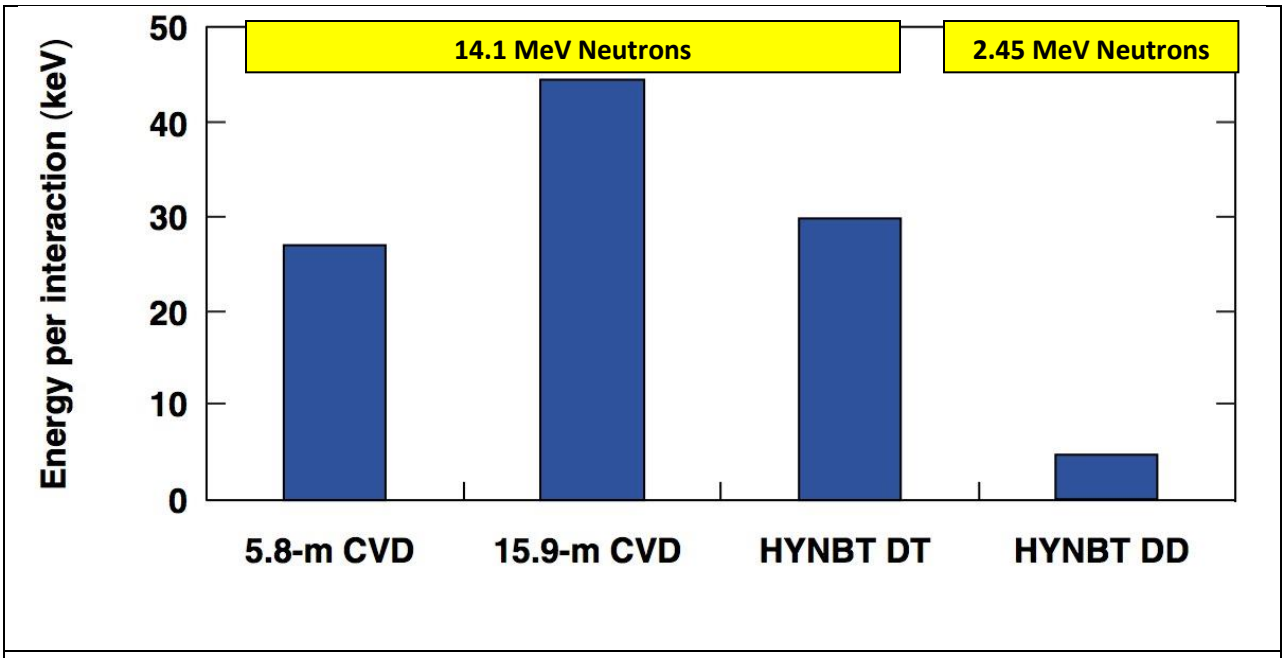

Figure 7: Energy deposited per neutron interaction in CVD diamond detectors. These values are the result of the application of a model that incorporates a variety of factors including detector location and thickness, neutron-carbon cross sections, and signal data analyzed in MATLAB.

Based on this data, the greatest deposited energy per neutron interaction occurs in the 15.9-m CVD detector. Directly comparing the data from the HYNBT campaign, the energy deposited from the DT reaction was 29.9 keV and the energy deposited from the DD reaction was 4.84 keV. This finding is supported by the fact that DD neutrons are emitted with lower energy and have a lower reaction cross-section in diamond.

VIII. Effective thickness of detectors

A final measure of detector performance is effective thickness, a value that acts as a measure of charge collection efficiency. Essentially, the effective thickness represents a fraction of the total thickness of the CVD diamond wafer and is indicative of the fabrication quality and detection capabilities of the detector. The effective thickness was calculated using a modified equation from a study by Coropceanu et al. as follows[7]:

$$L_{eff} = \tau * \mu * \frac{V}{L} \quad (6)$$

where τ represents the signal rise time calculated by determining the time from 10% of the signal maximum to 90% of the signal maximum, μ represents the electron mobility in diamond, L represents the actual thickness of the wafer, and V represents the bias voltage. The effective thickness is illustrated in **Fig. 8.**

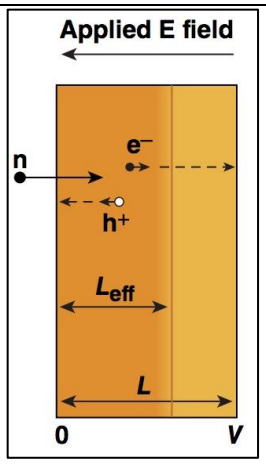

Figure 8: Rough visualization of effective thickness and the parameters *L* and V used in its calculation. Effective thickness is typically a fraction of the total thickness of the detector.

A MATLAB program was used to calculate the signal rise time. The signal for the 5.8-m CVD diamond detector is shown in **Fig. 9** together with an illustration of how the signal rise time is obtained.

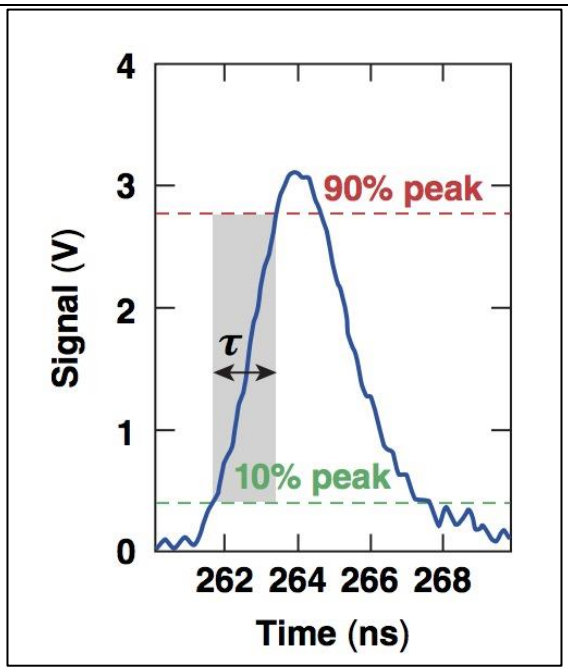

Figure 9: 10%-90% rise time signal analysis of a signal obtained from the 5.8-m CVD dataset. The shaded area indicates the signal increasing between 10% and 90% of the maximum.

Equation 6 was applied to the four data sets previously analyzed to determine the effective thickness of each of the four CVD diamond detectors. These data are shown in **Fig 10.**

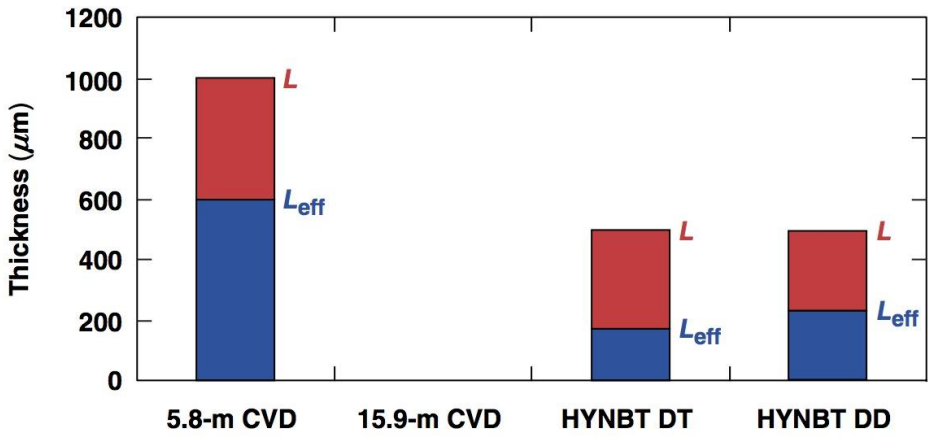

Figure 10: Effective thicknesses of three CVD detector configurations. The 5.8 m CVD detector exhibits the greatest charge collection efficiency since the ratio of effective thickness to total thickness is greatest (0.6).

It was not possible to calculate rise-time values of the 15.9-m CVD detector due to low signal amplitude and high noise. As a result, it was not possible to calculate the effective thickness of this detector.

The fact that the effective thickness is a fraction of the total thickness in each case provides an argument for creating thinner layers of diamonds for future detectors. Reducing the distance between electrodes by making thinner CVD layers reduces the probability that charge carriers will recombine within the lattice as they travel towards the electrodes. Recombination is problematic since it reduces the signal and distorts the data. The results shown in **Fig. 10** provide justification for creating a detection system that consists of several thin CVD wafers stacked together with electrodes interspersed between the layers.

IX. Conclusion

This study represents the creation and application of a simple mathematical model to quantify the energy deposition per neutron interaction in CVD diamond detectors. The model is phenomenological and can be applied to datasets obtained from CVD diamond detectors at other facilities as well as OMEGA. The model was applied to four datasets obtained from CVD diamond detectors installed on OMEGA in 2005 and 2015. The results indicate that DD neutrons deposit significantly less energy into these detectors as compared with DT neutrons. Furthermore, the second part of study focused on effective thickness reveals the possibility to use thinner detectors to increase charge collection efficiency.

The next area of interest in the field of neutron detection is the creation of a multi-capacity CVD diamond detector that is capable of detecting lower-energy thermal neutrons. Currently, these neutrons have very low cross sections for reactions with carbon nuclei and thus do not contribute significantly to electron-hole pair generation in CVD diamond alone. Future studies will consider the use of a lithium-fluoride layer stacked above the CVD diamond since the LiF layer is capable of detecting lower-energy neutrons. Stacked CVD diamond detectors are a potentially viable means to further increase signal resolution.

X. Acknowledgements

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