

CVD diamond detectors for current mode neutron time-of-flight spectroscopy at OMEGA/NIF

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ABSTRACT

We have performed pulsed neutron and pulsed laser tests of a CVD diamond detector manufactured from DIAFILM, a commercial grade of CVD diamond. The laser tests were performed at the short pulse UV laser at Bechtel Nevada in Livermore, CA. The pulsed neutrons were provided by DT capsule implosions at the OMEGA laser fusion facility in Rochester, NY. From these tests, we have determined the impulse response to be 250 ps fwhm for an applied E-field of 500 V/mm. Additionally, we have determined the sensitivity to be 2.4 mA/W at 500 V/mm and 4.0 mA/W at 1000 V/mm. These values are approximately 2 to 5x times higher than those reported for natural Type IIa diamond at similar E-field and thickness (1mm). These characteristics allow us to conceive of a neutron time-of-flight current mode spectrometer based on CVD diamond. Such an instrument would sit inside the laser fusion target chamber close to target chamber center (TCC), and would record neutron spectra fast enough such that backscattered neutrons and γ rays from the target chamber wall would not be a concern. The acquired neutron spectra could then be used to extract DD fuel areal density from the downscattered secondary to secondary ratio.

Keywords: CVD diamond detector, neutron spectrometer, laser fusion diagnostic, fuel areal density

1. INTRODUCTION

Fuel areal density, $\langle \rho r \rangle$, is an important parameter of a laser fusion implosion [1]. For DD fuel, it has been suggested [2] that measuring the downscattered secondary to secondary neutron ratio might be a good technique to extract $\langle \rho r \rangle$. According to capsule implosion simulations that we have performed (using LLNL codes), the downscattered secondary to secondary neutron ratio is proportional to $\langle \rho r \rangle$ over a large yield range (one that encompasses both OMEGA and NIF). Furthermore, the ratio is temperature insensitive, and can be readily extracted from a measured neutron spectrum. Figure 1 shows a capsule implosion simulation of an unmixed, non-igniting, DD cryo shot at OMEGA. If we define R to be the neutron yield ratio of the downscattered secondaries (4-10 MeV) to the secondaries (12-17 MeV), we can then determine the areal density as follows:

$$\langle \rho r \rangle_{\text{DD}} \approx 9.2 R \text{ g/cm}^2 \quad (1)$$

However, measurement of a neutron spectrum as shown in Figure 1 is a non-trivial task. A detector dynamic range that spans many orders of magnitude is required. Furthermore, background effects can be a real problem. For example, in a previous conceptual study [3], we looked at the possibility of measuring R with the MEDUSA neutron spectrometer array [4] located 19m from TCC at OMEGA. However, neutron transport simulations with COG [5] showed a fairly severe background problem in the downscattered secondary region (with a large contribution coming from neutron scattering at the target chamber wall). This, coupled with the limited dynamic range of the instrument, indicated that an accurate extraction of R with the "single hit" technique would be quite difficult.

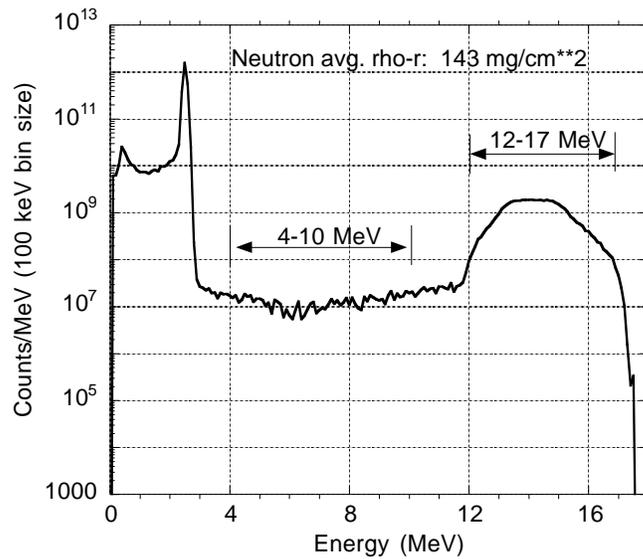


Figure 1: Simulated neutron spectrum from imploding DD cryo capsule on OMEGA.

An alternative approach is current mode detection. In fact, current mode detectors are already an important part of the diagnostic program at OMEGA [6,7]. For the present application, one could envision placing a fast current mode detector near TCC, and thus hope to record an entire DD neutron spectrum before scattered neutrons and neutron induced γ rays from chamber wall arrive. Since space near TCC is limited, one would like to minimize size and maximize sensitivity of the proposed current mode detector. For small size, solid state detectors generally have faster decay times and higher sensitivity (signal per energy deposited) than scintillator systems. Silicon is a common choice for a solid state detector, but its response is too slow for the current application. Diamond and neutron damaged GaAs are other options. We choose diamond, because for a given temporal response, diamond has been shown to have the better neutron sensitivity [8]. It has also been shown to have the necessary dynamic range of 10^5 [9]. The fact that diamond is low z makes it relatively insensitive to x-rays/ γ -rays, which is good for this application. Furthermore, diamond has the highest lattice density of any known material, and its strong bonds make it very radiation hard [10,11] and able to withstand even a harsh NIF-type environment without degrading in performance. Additionally, its large bandgap of 5.5 eV makes it relatively insensitive to scattered laser light.

Natural type IIa diamond detectors have been employed at laser fusion facilities in the past, both for x-ray detection [9,12] and neutron detection [8]. Unfortunately, natural diamond is expensive, and is commercially available only in small crystals. A modern day alternative is CVD diamond, which is grown in the laboratory. It can now be purchased commercially in large disks or plates, and the cost is very low compared with natural diamond. Furthermore, some research grade CVD diamonds have been shown to have significantly better electrical quality, and thus better sensitivity, than natural diamond [13]. In this report, we discuss results obtained with a commercially available type of CVD diamond known as DIAFILM [14,15].

2. DETECTOR FABRICATION

The Chemical Vapor Deposition (CVD) diamond wafers used in the current work were grown at the DeBeers Industrial Diamond Division in the UK. The synthesis technique was microwave assisted plasma deposition in a methane, hydrogen, oxygen atmosphere [14]. This process produces polycrystalline films with the grains oriented parallel to the growth direction. Once the substrates are removed, the freestanding wafers are then polished at Drukker International in the Netherlands, and can be purchased commercially in the United States as "DIAFILM" through Harris International, New York. We purchased several "optical quality", cylindrical, DIAFILM wafers with 10mm diameter and 1mm thickness.

As delivered, the diamond wafers had a mildly conducting substance on the sides which resisted acid cleaning and proved difficult to remove. For this reason, we had the sides of the wafer specially polished on a diamond coated turning wheel at

the LLNL optics shop. Following this, they were cleaned in an acid bath and rinsed with de-ionized water. The electrical contacts were then evaporated on at the LLNL Micro Technology Center. We used 100 Angstroms Cr and 5000 Angstroms Au on each side. The shape of these ohmic contacts were 8mm circles, thus leaving a 1mm clear ring around the edges. This helped to prevent surface breakdown when HV was applied. Following evaporation, thin Indium contact pads (130 μ) were applied to each side, and the sandwiched wafer was then placed in a holder. The geometry of the holder is illustrated in Figure 2. Using a TEKTRONIX type 130 L-C meter, the capacitance of detector and holder was measured to be 5 pF.

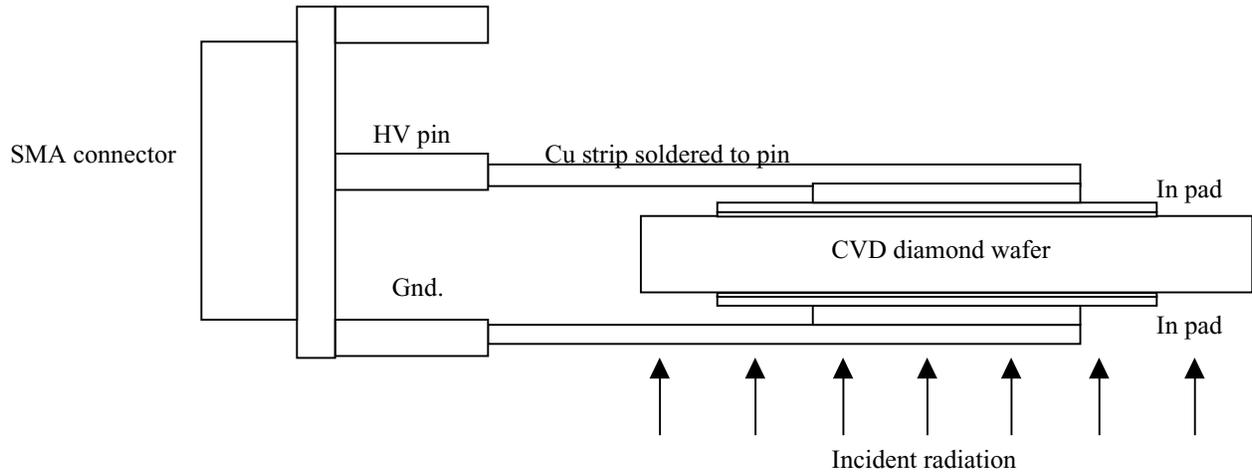


Figure 2: CVD diamond detector and holder. The CVD wafer is sandwiched between two In contact pads. The assembly is held together by tension in two opposing Cu strips. A thin Cu housing structure (not shown) provides a certain degree of optical and electromagnetic shielding. The signal cable attaches to back of SMA connector.

3. DETECTOR OPERATION

For standard operation, the signal cable coming out of the SMA connector is routed to a high voltage, high speed, bias-T (Picosecond Pulse Labs, model 5531) where up to 1000V potential can be applied. The signal cable coming out of the bias-T is then routed to a fast scope. For the laser tests, a 3 GHz TEKTRONIX TDS694c was used, while for the neutron tests, we employed a 1 GHz TDS684b. All inputs to scope were terminated in 50 Ω . In the case of the neutron tests, the input signal was teed-off to allow digitization of two scope channels with different vertical scales. Figure 3 shows the electronic set up. With no radiation incident on the detector, only scope noise of 160 μ V RMS is seen (i.e. there is no leakage current evident even at most sensitive scale). This is to be expected due to the very high resistivity of diamond (> 10¹¹ Ω cm).

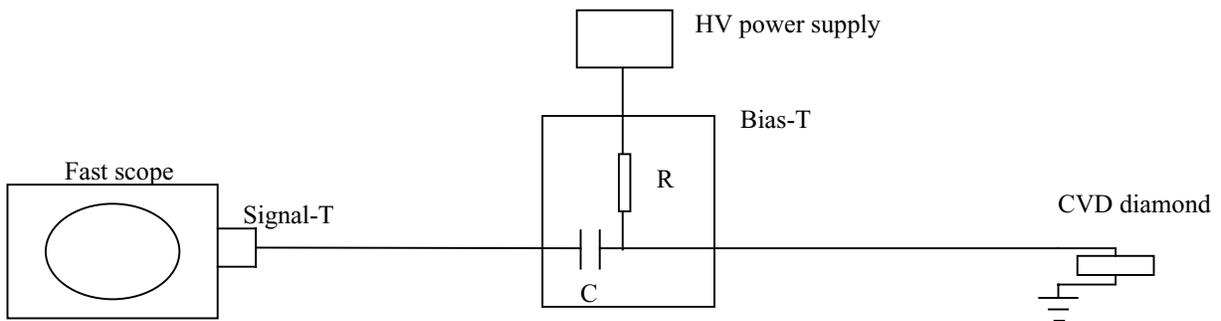


Figure 3: Schematic of electrical set up for neutron tests. Both inputs to scope are terminated in 50 Ω .

Ultra-violet laser photons (6 eV) and/or fast neutrons (14 MeV) which are incident on the diamond will induce a signal by generating electron-hole pairs which then drift apart under the applied E-field. For the photons, the interaction is a photoelectric event with a valence electron. In the case of 14 MeV neutrons, there are three primary mechanisms that generate electron hole pairs: elastic scattering generating knock-on C nuclei; inelastic scattering also generating knock-on C nuclei plus an escape γ ray; and three α breakup of C. Table I shows cross section, σ_m , and average energy deposited, E_m , for each primary mechanism. Table II shows the same information for 2.5 MeV neutrons. Also shown in the tables is the total cross section for all processes, σ_{tot} , and the total average energy deposition, E_{av} , which is the cross section weighted average over the three primary mechanisms.

	(n,n)	(n,n' γ)	(n,n2 α) α	All processes
σ_m (10^{-24} cm 2)	0.80	0.23	0.19	$\sigma_{tot}= 1.30$
E_m (MeV)	0.81	1.30	5.60	$E_{av} = 1.64$

Table I: Parameters for 14 MeV neutrons on C [16].

	(n,n)	(n,n' γ)	(n,n2 α) α	All processes
σ_m (10^{-24} cm 2)	1.60	0.0	0.0	$\sigma_{tot}= 1.60$
E_m (MeV)	0.37	0.0	0.0	$E_{av} = 0.37$

Table II: Parameters for 2.5 MeV neutrons on C [16].

For incident radiation at least a few times above the bandgap, the average energy to create one electron-hole pair (ϵ) in diamond is known to be 13 eV [17]. The electron hole pairs that are generated will be swept apart under the applied field, but will generally trap before reaching the contacts. The average separation distance (d) of an electron-hole pair is [18]:

$$d = (\mu_e \tau_e E + \mu_h \tau_h E) \propto 1/N_t \quad (2)$$

where $\mu_{e,h}$ is the electron/hole mobility, $\tau_{e,h}$ is the electron/hole lifetime, E is the applied electric field, and N_t is the concentration of trapping sites in the crystal.

Since d is inversely proportional to the trapping site concentration, its value is commonly taken as an indicator of the electrical quality of a crystal (a higher value of d indicating better quality). We can determine the value of d for a given sample of thickness, T , by using the following approximate relation (valid for $d \ll T$) [18]:

$$d \approx (Q_M / Q_T) T, \quad (3)$$

where Q_T is the total charge liberated by the incident radiation and Q_M is the total induced charge that is actually measured by integrating the current signal at the scope.¹ The value of Q_T (in Coulombs) can be determined by the relation:

$$Q_T = (E_{dep}/\epsilon) (1.6 \times 10^{-19}), \quad (4)$$

where E_{dep} (in same units as ϵ) is the total energy deposited by the incident radiation (a quantity that must be calculated).

4. MEASUREMENTS

Figure 4 shows two consecutive traces acquired at the short pulse (150 fs) 200 nm laser facility at Bechtel Nevada in Livermore. The bias voltage on the CVD diamond was 500 V ($E=500$ V/mm). The voltage scale has been normalized to allow shape comparison of the two traces. The fwhm of the responses are seen to be 250 ps, which is equivalent to the calculated RC time constant of the electrical circuit. The high side tail is likely due to trapping of the slow moving holes.

¹ It can be shown that while Q_T is implicitly dependent on detector area (A) and thickness (T), Q_M is implicitly dependent only on A and E , not T . Therefore, as expected, we see that d will be a function of E but not T .

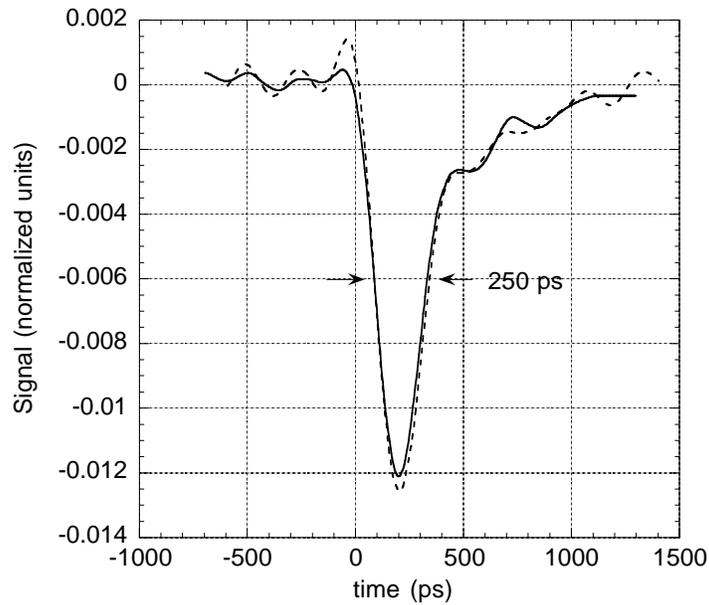


Figure 4: Response function of CVD diamond detector to 150 fs UV laser pulse. Two consecutive traces are shown. Applied E-field was 500 V/mm.

Although the charge carrier velocities are known to be unsaturated at an e-field of 500 V/mm [18], the bias was not increased further at the time of this measurement due to concerns about surface breakdown. However, subsequent tests (outlined below) have shown that the detector can take 1000 V bias with no breakdown. Based on previous tests we have done with natural diamond, it is expected that the time response will further narrow at the higher bias, especially the high side tail.

Figures 5,6, and 7 show the response of the CVD diamond detector (at 500 V/mm) to 14 MeV neutrons from DT implosions at the OMEGA laser fusion facility. For Figs 5 and 6, the detector was at 1.7m from TCC, where it was bolted to a 1.6cm thick Al subport on the target chamber wall (in Fig.6, ~1cm of plastic shielding was added between detector and chamber).

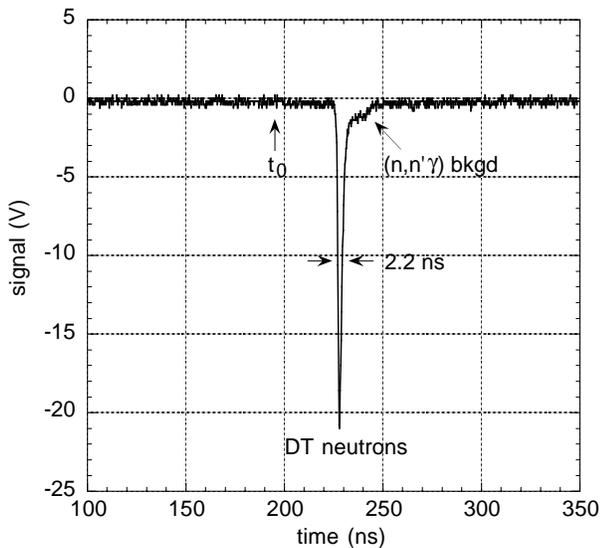


Figure 5: Shot 23458. Total neutron yield (Y) was 6.9×10^{13} . Vertical scale corrects for $\times 10$ attenuator that was present. The implosion time (t_0) is at 195 ns.

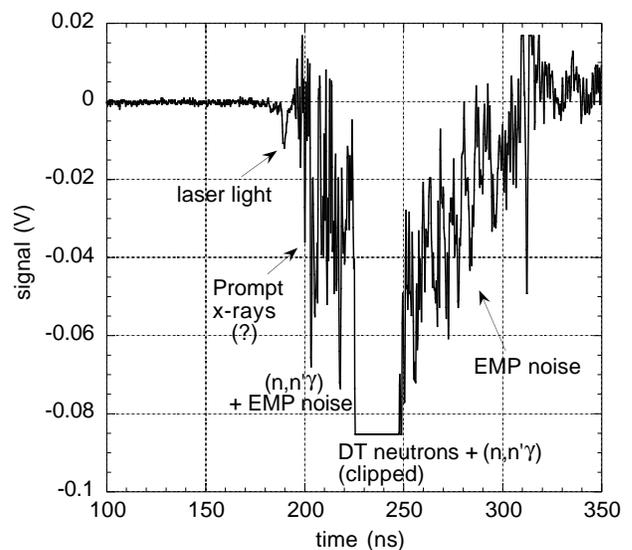


Figure 6: Shot 23476 with $Y=2.4 \times 10^{13}$ and $t_0=195$ ns. Vertical scale is expanded in this picture to show EMP noise and other features. DT peak is offscale.

Figure 7 shows data acquired at a different location: nominally ~8m from TCC inside a small Pb housing structure which sits on the floor of the OMEGA target bay. Because different electronics were used for this set up, the t_0 time is now estimated to be at ~272 ns. Due to the extremely sensitive scale and the lack of substantial EMP noise (probably due to distance from chamber and Pb shielding) the $(n,n'\gamma)$ pulses, from somewhere inside target chamber, are now clearly visible around 300 ns. The large 14 MeV neutron pulse is then seen at 432 ns, which quickly goes way off scale and is clipped.

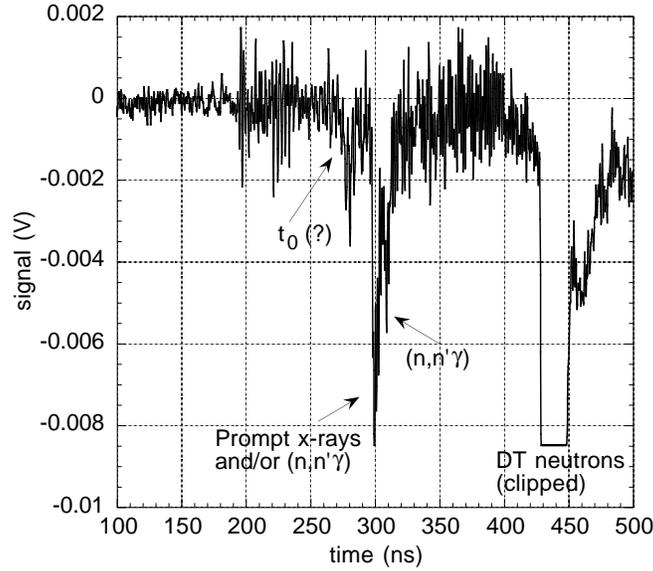


Figure 7: Shot 23464 with $Y=7 \times 10^{13}$ and $t_0 \sim 272$ ns. Note the low quiescent noise before 200 ns.

5. SENSITIVITY CALCULATION

Using the data shown in Figure 5, a detector sensitivity for the CVD diamond can be calculated. The standard units for photodetector sensitivity are A/W (amps of current generated per watt of deposited power). These units are exactly equal to C/J (coulombs of measured charge per joule of deposited energy). Thus, we can define the sensitivity, S , in A/W, as:

$$S = Q_M / (1.6 \times 10^{-19} \times E_{\text{dep}}), \quad (5)$$

with Q_M in coulombs and E_{dep} in eV.

The quantity E_{dep} (in eV) can be calculated using the following formula:

$$E_{\text{dep}} = (d\Omega/4\pi)YA(1-e^{-\sigma Tn})E_{\text{av}}, \quad (6)$$

where $d\Omega$ is the detector solid angle (steradians), Y is the total neutron yield for a given shot, σ is the total cross section (in cm^2) for neutrons interacting in diamond, A is a factor to account for neutron scattering in/out of detector solid angle due to support cover ($=0.92$ from COG simulations), T is the detector thickness, n is the lattice density of diamond in \#atoms/cm^3 , and E_{av} is the average energy deposited per neutron interaction (in eV).

For future reference, we note that (for $d \ll T$):

$$S \approx d / (T\epsilon), \quad (7)$$

where d is in microns, S is in A/W, T is in microns, and ϵ is in eV.²

In order to calculate a sensitivity for our CVD diamond detector we use equations (5) and (6), and obtain Q_M by integrating the peak in Fig.5. The contribution from $(n,n'\gamma)$ background is subtracted off. The final result: $S=2.4$ mA/W at an $E=500$ V/mm and $T=1$ mm. Subsequent measurements, with the detector at the ~ 8 m location, have found that raising the E -field to 1000 V/mm improved sensitivity by 66%. This indicates that the sensitivity at 1000 V/mm (and $T=1$ mm) is: $S=4.0$ mA/W. This corresponds to $d = 52 \mu$. The primary uncertainty in the determination of S and d is thought to be the calculation of energy deposited in the diamond, which is estimated to be accurate to within 20%. Table III compares the current values of S and d with values previously reported for natural Type IIa diamond detectors at similar E -fields and detector thickness.

	Current CVD results	Kania et al. [9]	Garconnet et al. [8] ³	Zhao [18]
Sensitivity (at 500 V/mm)	2.4 mA/W Pulsed MeVneutrons	-----	1.4 mA/W Pulsed MeVneutrons	1.2 mA/W Charged particles
d (at 500 V/mm)	31 μ	-----	18 μ	16 μ
Sensitivity (at 1000 V/mm)	4.0 mA/W	0.8 mA/W Pulsed keV x-rays	-----	2.0 mA/W
d (at 1000 V/mm)	52 μ	10 μ	-----	26 μ

Table III: Current CVD diamond results compared with some previously reported natural Type IIa diamond results. All numbers listed here are for a detector thickness, T , of 1mm.

The sensitivity units A/W are useful for general comparisons because they are independent of neutron energy and detector surface area. However, for practical applications, it is convenient to have units that are specific for a given energy and a given detector. For this reason, we list here the sensitivity of the current CVD diamond detector in units of C/n (Coulombs per incident neutron): $S=2.4 \times 10^{-17}$ C/n for 14 MeV neutrons; and $S=6.7 \times 10^{-18}$ C/n for 2.5 MeV neutrons. Both of these values are at $E=1000$ V/mm and $T=1$ mm. These units can be further simplified if we make the assumption that 60% of total signal strength lies in a gaussian shaped peak (the rest going into high side tail). We can then estimate the peak voltage on a 50 Ω terminated scope as: $S \sim 0.7 \mu\text{V}/\text{n}/\text{ns}$ (μV per incident neutron per ns of signal fwhm) for 14 MeV neutrons; and $S \sim 0.2 \mu\text{V}/\text{n}/\text{ns}$ for 2.5 MeV neutrons. If the set up in Figure 3 is used, the numbers will be 0.5x smaller due to the signal- T .

6. CONCLUSIONS

We have investigated the response of a CVD diamond detector to pulsed UV laser photons & pulsed 14 MeV neutrons in order to evaluate its potential as a laser fusion diagnostic. The type of CVD diamond used was optical quality DIAFILM, a commercially available material that can be purchased in the USA through Harris International, NY. Our results indicated a response time of 250ps fwhm at 500 V/mm, and a sensitivity of 2.4 mA/W at 500 V/mm and 4.0 mA/W at 1000 V/mm. These sensitivity values, for 1mm detector thickness, are about 2-5x higher than reported values for natural type IIa diamond.

Worldwide interest and research in CVD diamond detectors is growing. During the past few years, some particularly interesting effects have been reported by researchers in the high energy physics community [13]. One of these is the so called "priming" or "pumping" effect, whereby a heavily irradiated CVD diamond crystal actually improves in electrical

² This equation demonstrates that S is not only dependent on E (through d), but also on detector thickness, T . The dependence on T disappears in cases where $d > T$ (not typical for diamond detectors since one usually desires large T to improve quantum statistics).

³ S value of [8] was converted from reported units into A/W. This required calculating energy deposition in their detector for given pb shielding configuration. Calculation is assumed to be accurate to within 20%. In addition, for the purpose of comparison, it was necessary to convert S value of [8] from $T=2$ mm (actual size) to $T=1$ mm. This was done by multiplying their result by a factor of two.

quality (d increasing by as much as a factor of two). This effect is thought to be due to the filling of potential trapping sites by electrons and holes. The effect can be reversed by irradiation with visible light. Another interesting development is the high crystal quality that has been reported. By working collaboratively with CVD diamond growers, some researchers have reported d values as high as 250μ at 1000 V/mm . Unfortunately, these "research grade" CVD diamonds are not known to be commercially available.

Regarding the use of CVD diamond as a laser fusion diagnostic, here are some ideas for future work:

- 1) Explore the sensitivity and temporal response of current CVD diamond detector vs. applied E-field. If E-field can be increased substantially past 1000 V/mm without surface breakdown, large gains in sensitivity may be possible [18,19].
- 2) Explore the degree to which sensitivity varies for different samples of DIAFILM.
- 3) Test the high quality "research grade" CVD diamonds in a laser fusion environment (assuming samples can be obtained). Investigating temporal response will be of particular importance.
- 4) Explore shielding solutions for EMP noise inside laser fusion target chamber. Preliminary results, to be discussed in a future paper, indicate that isolating detector ground from chamber ground, and enclosing detector and cabling in a separately grounded metal shield, can reduce EMP noise to as low as $\sim 1 \text{ mV}$.

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