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Sensitivity of chemical vapor deposition diamonds to DD and DT neutrons at OMEGA and the National Ignition Facility

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The particle-time-of-flight (pTOF) detector at the National Ignition Facility (NIF) is used routinely to measure nuclear bang-times in inertial confinement fusion implosions. The active detector medium in pTOF is a chemical vapor deposition diamond. Calibration of the detectors sensitivity to neutrons and protons would allow measurement of nuclear bang times and hot spot areal density (ρR) on a single diagnostic. This study utilizes data collected at both NIF and Omega in an attempt to determine pTOF's absolute sensitivity to neutrons. At Omega pTOF's sensitivity to DT-n is found to be stable to within 8% at different bias voltages. At the NIF pTOF's sensitivity to DD-n varies by up to 59%. This variability must be decreased substantially for pTOF to function as a neutron yield detector at the NIF. Some possible causes of this variability are ruled out. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4960071]

I. BACKGROUND AND MOTIVATION

Understanding nuclear reaction history and bang times in inertial confinement fusion (ICF) experiments is critical for developing simulations and theories to further constrain modeling of ICF experiments.[1,2] In an ICF implosion at the National Ignition Facility (NIF)[3] shocks are launched into the ablator by a laser pulse. These shocks coalesce at the fuel-shell interface and then converge at the center of the implosion,[4] which causes significant heating and a period of nuclear burn ("shock phase"), followed by a compression phase due to the imploding shell. The particle-time-of-flight (pTOF)[5] and the magnetic particle-time-of-flight (magPTOF)[6] detectors were developed at MIT to measure the shock and compression bang-times in NIF implosions. These two measurements in combination with areal density (ρR) measurements from wedge range filters (WRFs)[7] can be used to guide theory and constrain simulations.

The pTOF is a chemical vapor deposition (CVD) diamond based detector.[8,9] Due to its fast rise, shock bang-time can be measured to an accuracy ~50 ps. Currently, pTOF and magPTOF are standard diagnostics at the NIF and can be called out to measure bang-times on a variety of experiments. As a bang time detector, pTOF has proven its usefulness.[10–12] Next, we would like to extend the application of this detector to also measure particle yields. The fuel areal density (ρR) in deuterium gas filled ICF surrogate implosions can be inferred from the ratio of primary DD-n to secondary fusion products, both D^3He-p and DT-n.[13] If the sensitivity of pTOF to protons and neutrons is determined, the detector could be used to diagnose fuel ρR. This would allow the measurement of shock-bang time and fuel ρR using a single diagnostic and along a single line-of-sight.

II. EXPERIMENTS

Experiments at Omega were conducted using a 300 μm thick CVD diamond based pTOF detector exposed to DT-n. Figure 1 shows the experimental setup used to collect DT-n data during a variety of implosion types across many days. The diamond was placed inside the steel walled re-entrant tube 170 cm from target chamber center (TCC) and biased to several different voltages from 250 to 1500 V. The signal was relayed by a coaxial cable, filtered through a bias-T, and recorded by a Tektronix DPO70604B oscilloscope. Using the setup shown in Figure 1 allowed the collection of a diverse set of data for calibration purposes.

A signal trace from pTOF exposed to DT-n on OMEGA is shown in Figure 2. This is an example of data used to determine the sensitivity of the detector. A numeric integral over the signal region is performed. The signal integral should correlate to the number of neutrons interacting with the detector volume. To check this, the signal integrals were normalized to the DT-n yield as determined by the nTOFs.

The pTOF detector is regularly used at the NIF to measure nuclear bang times. As such there is already a large database (~150) of pTOF signals under a variety of conditions. In this work three detectors with 200 μm thick diamonds, biased to 250 V and exposed to DD-n were used. It would be useful to make a direct comparison of DT-n sensitivity at OMEGA and the NIF; however, not enough DT-n pTOF traces have been collected at the NIF to make a significant comparison. Data

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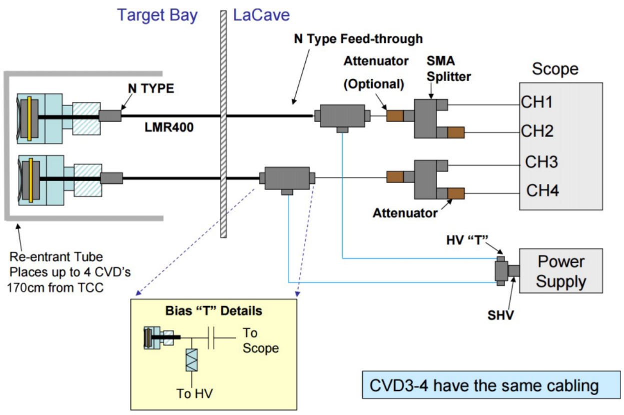

FIG. 1. Schematic of pTOF fielded in the re-entrant tube at Omega.

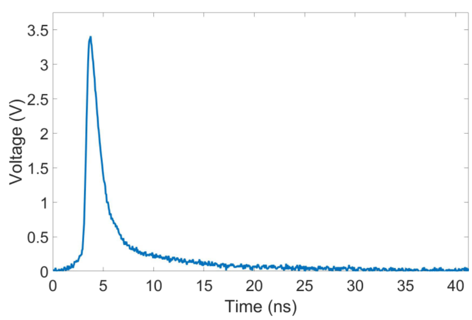

FIG. 2. Response of pTOF 300H to DT-n in the re-entrant tube at 500 V on OMEGA shot 81328 (05/03/16). This shot had a DT-n yield of $2.12\times10^{+13}$ as measured by the nTOFs. pTOF 300H showed a sensitivity of 1.66×10^{-7} V ns/DT-n.

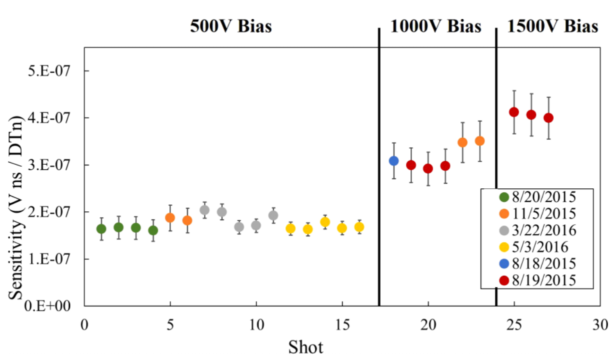

FIG. 3. Sensitivity of pTOF 300H to DT-n at various bias voltages, across several shot days at OMEGA.

collection is done with a combination of an FTD10000 and Tektronix TDS6604B oscilloscope.[5]

For the NIF data, a similar analysis procedure as described for OMEGA data was conducted. Signal traces exhibiting unusual features (dominant x–ray signals, ringing attributed to EMP, or significant cable reflections) and with signals close to the noise floor were not included in this study.

III. RESULTS

A. OMEGA data

The pTOF detector shows excellent shot to shot consistency when used at OMEGA to measure DTn. Figure 3 shows a summary of the sensitivity as calculated on several shots across shot days and at different bias voltages. Error bars are dominated by yield uncertainty as reported by OMEGA, but also incorporate error from numerical integration. The sensitivity is stable to within 8% at each bias voltage, and is consistent within the error bars. Table I shows a summary of sensitivity and uncertainty at each bias.

TABLE I. Summary of pTOF 300H sensitivity to DT-n at OMEGA.

Bias voltage (V)	Sensitivity (V ns/DT-n)	Uncertainty (%)	Standard deviation (%)
500	1.74×10^{-7}	2.4	7.7
1000	3.13×10^{-7}	5.0	7.7
1500	4.06×10^{-7}	6.4	1.3

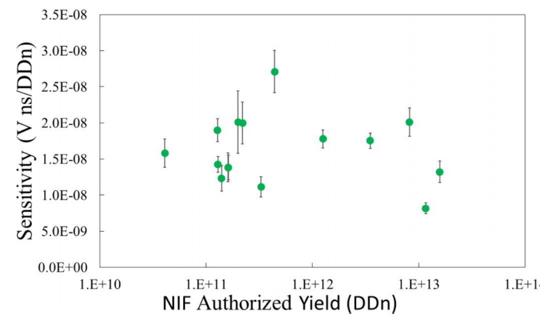

FIG. 4. Sensitivity of detector 200R to DD-n at 250 V bias plotted versus the NIF authorized DD-n yield.

TABLE II. Summary of the DD-n sensitivity of 200 μm pTOFs biased to 250 V at the NIF.

pTOF ID	Sensitivity (V ns/DD-n)	Standard deviation (%)
200R	1.40×10^{-8}	28
200M	4.07×10^{-9}	59
200B	1.82×10^{-8}	20

B. NIF data

On the NIF, the sensitivity of pTOF to DD-n is highly variable. Figure 4 shows a plot of sensitivity of a single detector (200R) at a variety of yields. These data have a standard deviation of 28%. Similar analysis of data from two other detectors, 200M (11 data points) and 200B (5 data points), was conducted. A summary of the standard deviations is presented in Table II. The spread in the data is larger than the error bars, which are dominated by yield uncertainty as reported by the NIF.

The goal of this study is to calibrate pTOF so that it can be used to measure DT-n yield at the NIF. In its current state, no such calibration can be obtained. Although the two measurements cannot be directly compared, the stability of 300H when exposed to DT-n at OMEGA indicates that it may be a procedural or environmental issue causing variability at the NIF. If this source of variability can be identified and remedied, pTOF may be used to measure yields in the future.

IV. POSSIBLE SOURCES OF INSTABILITY

CVD diamond is known to be radiation hard, but large neutron doses could cause a non-linear response, i.e., the

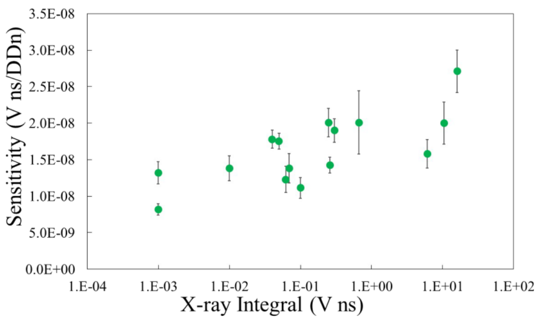

FIG. 5. Sensitivity of detector 200R to DD-n at 250 V bias plotted versus the size of the preceding X-ray signal.

charge freed per neutron could vary as more neutrons interact with the diamond. Such effects are only expected with signals at 10% of the detector bias or higher (≥25 V). No correlation was found when plotting sensitivity versus particle yield as shown in Figure 4. This makes sense as none of these signals are above 25 V.

On standard pTOF traces, the particle signal is preceded by an X-ray signal of varying amplitude. It was theorized that the detector may not have time to recover to a steady state between the two signals and that a larger X-ray signal would correlate to a lower sensitivity, due to a lower apparent bias voltage. This theory was tested by plotting the detector sensitivity versus the integral of the X-ray signal as shown in Figure 5. No correlation was found and therefore this theory has been ruled out.

Currently, we are investigating the time left at bias before shot time as a possible source of variability. At OMEGA the bias is brought up hours before the shot, if not the night before, while on the NIF bias is brought up about 2 min before shot. Some tests of this theory have been performed, but more rigorous experimentation is necessary before we may draw any conclusions.

A final, yet to be investigated, source of variability could result from pTOF being removed and reinstalled every time it is fielded. Removing and reinstalling the detector could cause changes in the internal connection, effecting sensitivity. South Pole Bang Time (SPBT) is a CVD diamond based X-ray bang time detector at the NIF. This detector is a permanent fixture, so it is not removed between shots. Data from one of the SPBT diamonds was compiled to determine if it could be used to measure yields. A summary of these data is shown in Figure 6. In this case it was found that the diamonds sensitivity was stable. This indicates that removal and reinstallation may be a cause of variability, however, this is not a direct comparison as this SPBT diamond is doped with impurities, to increase response time, while pTOF diamonds are not. The SPBT diamond is also fielded at a much higher bias field of 6 kV/mm compared to pTOF at 1.25 kV/mm. In the future, experiments will be conducted to test this theory.

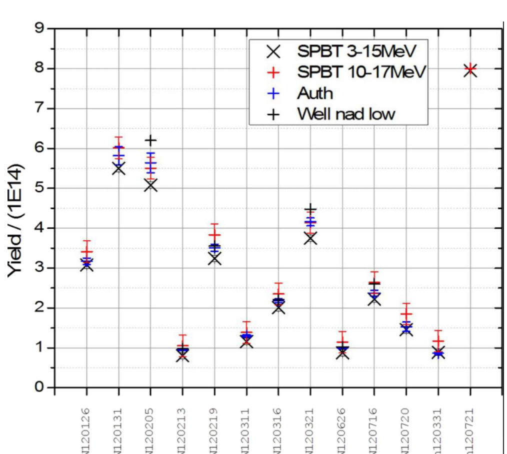

FIG. 6. DT-n yield as measured by two different SPBT diamonds is shown to be in general agreement with the NIF authorized values.

V. SUMMARY AND CONCLUSIONS

Data with pTOF detector 300H at Omega show a robust DT-n sensitivity of 1.74×10^{-7} V ns/DTn. In the future, it is likely that this detector could be used to measure DT-n yields at Omega. All three NIF detectors that were analyzed had highly variable DD-n sensitivities with up to 59% standard deviation. The goal of this project was to determine a calibration for the detectors used at NIF so that they could be used to measure yields. In this current state, none of the NIF detectors could be used to reliably measure DD-n yield. Some possible sources of sensitivity instability have been explored and ruled out (preceding x-ray signal and non-linear sensitivity), while others require further investigation (time at bias before shot and reinstallation between experiments).

VI. FUTURE WORK

Data will continue to be collected at Omega in the reentrant tube using 300H and several other detectors to increase statistics and explore detector stability. Experiments will be performed in order to quantify the effects of varying the time between the bias voltage being brought up and shot time as well as effects of removal and reinstallation.

Moving forward we would also like to establish the sensitivity of pTOF to D^3He-p, x-rays, and explore the stability of pTOF's IRF. At the end of this sequence of studies we hope to make pTOF a fully characterized and robust particle yield detector for the NIF.

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