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A novel particle Time Of Flight (pTOF) diagnostic for measurements of shock- and compression-bang times in D^3He and DT implosions at the NIF

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The particle-time-of-flight (pTOF) diagnostic, fielded alongside a Wedge Range-Filter (WRF) proton spectrometer, will provide an absolute timing for the shock-burn weighted ρR measurements that will validate the modeling of implosion dynamics at the National Ignition Facility (NIF). In the first phase of the project, pTOF has recorded accurate bang times in cryogenic DT, DT-Exploding Pusher and D^3He implosions using DD or DT neutrons with an accuracy better than ±70 ps. In the second phase of the project, a deflecting magnet will be incorporated into the pTOF design for simultaneous measurements of shock- and compression-bang times in D^3He-filled surrogate implosions using D^3He protons and DD-neutrons, respectively.

Nuclear burn diagnostics[1] provide crucial information for understanding the physics of Inertial Confinement Fusion[2] (ICF) experiments. In experiments at the National Ignition Facility (NIF),[3] shocks launched into the ablator by the laser pulse are timed to coalesce within the gas fill.[4] The combined shock transits to the center of the capsule and rebounds, heating the shocked gas and causing a period of nuclear burn ('shock bang') before compression by the imploding shell forms the hotspot ('compression burn'). The strength and timing of the combined shock are effected by the target geometry, shock timing, equations-of-state for the ablator and fuel, and preheat.[5] A measurement of the shock bang-time will guide understanding of the role of these components in the ignition campaign. In surrogate targets filled with D^3He gas, the ρR at shock bang-time is routinely determined from the energy downshift of the D^3He fusion protons measured by the Wedge Range Filter (WRF) diagnostic.[6] A measurement of the shock bang-time would greatly increase the value of this data by determining the ρR evolution of the capsule independent of simulations.

A CVD-diamond-based detector[7] is ideal for a novel measurement of the shock- and compression-bang times in implosions at the NIF. The detector is compact and vacuum-compatible, so it may be fielded close to the target to increase statistics and decrease time-of-flight uncertainty. A rapid detector rise-time allows timing accuracy better than ±50 ps. Furthermore, the detectors were found to be over 1000 times more sensitive to protons than neutrons. Since this value is comparable to the ratio of DD-neutron to D^3He-proton yield in SymCap and Convergent Ablator experiments at the NIF, a CVD-diamond based detector will simultaneously measure shock- and compression-bang time on a single diagnostic.

In this paper, the diagnostic design and implementation of pTOF at the NIF and data from the tuning campaigns in 2011 and 2012 are discussed. The paper is structured as follows: Section I discusses the current setup for pTOF. Section II discusses the analysis of pTOF data. Section III describes the method of calibration for the diagnostic. Section IV presents pTOF data from the tuning campaigns in 2011 and 2012. In Section V concluding remarks are made.

I. EXPERIMENTAL SETUP

A particle time-of-flight (pTOF) diagnostic has been implemented to measure neutron bang-times at the NIF. At 50 cm, pTOF is the closest nuclear bang-time diagnostic to target chamber center (TCC). This reduces uncertainties due to particle velocity and allows for accurate measurements of nuclear bang-times using DD-neutrons in surrogate D^3He-gas-filled implosions. An upgrade to the pTOF diagnostic is also being implemented for simultaneous and robust measurements of shock- and compression-bang times, using D^3He-protons and DD-neutrons, respectively.

The pTOF detector is sensitive to impulses of neutrons from the DT and DD fusion reactions, and protons from the D^3He fusion reaction. A circular, synthetic diamond wafer made by the chemical vapor deposition (CVD) technique is biased along its axis. Incident high-energy particles excite electron-hole pairs in the diamond volume, a fraction of which are collected by the bias field as a time-dependent current and recorded on an oscilloscope as a voltage impulse. The pTOF detectors are similar in operation to diamond-based neutron Time-of-Flight (nTOF) detectors at OMEGA and NIF[8] and the South Pole Bang Time (SPBT) system at NIF.[9]

The CVD-diamonds used are optical-quality, 200-μm

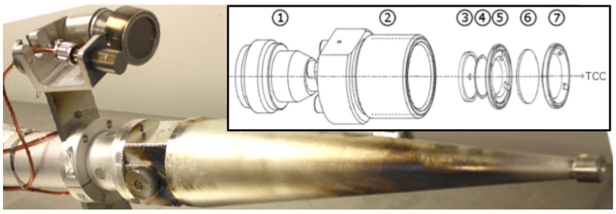

FIG. 1. The pTOF fielded on DIM (90,78) next to a WRF module. The detector is fielded with 2 cm W filtering. (inset) The pTOF detector consists of 1. N-type connector with biased pin, 2. brass housing, 3. ceramic insulator, 4. 200 μm thick, 10 mm diameter CVD-diamond wafer with electrodes, 5. electrode grounding ring aperture (8 mm ID), 6. configurable x-ray filtering, 7. filter cap.

thick samples with a diameter of 10 mm. The samples were acquired from Diamond Materials, GmbH.,[10] and were further processed at Lawrence Livermore National Laboratory (LLNL), where electrodes were deposited on the front and rear surfaces. The 1 μm thick, 9 mm diameter Au electrodes were deposited on top of an intermediate 200 Å Ti wetting layer. The diamonds are housed inside a brass assembly depicted in Fig 1. A rear electrode pin biases the sample, which is grounded to the housing by a ring-shaped front aperture. The aperture leaves 64% of the detector surface exposed.

In the first phase of the pTOF implementation, the diagnostic is fielded on a Diagnostic Instrument Manipulator (DIM)[11] located at ($\theta = 90$,$\phi = 78$) in the NIF chamber. The detector is fielded side-by-side with a Wedge-Range-Filter (WRF) proton spectrometer[12] at 50 cm from TCC, and is biased at -250 Volts. Fig 1 shows a photograph of a snout assembly with pTOF.

X-ray signals, primarily generated by laser-plasma interactions (LPI), are both observed and calculated[13] to dominate the DD-neutron and D^{3}He-proton signals for the pTOF detector at the NIF. To reduce the magnitude of the direct x-ray signal to the required level for accurate measurements of these species, a high-Z filter with an areal density of several tens of g/cm^2 is required. Such a filter stops any D^{3}He protons from reaching the detector. For this reason, the second phase of the pTOF implementation will include a permanent dipole magnet to deflect shock-bang protons onto the detector around a configurable line-of-sight filter with thickness ~2 cm.

Signals generated in the CVD diamond are transmitted from DIM (90,78) to the NIF mezzanine through 95 feet of low-loss LMR-400 cable. The signal is first recorded on an FTD10000 oscilloscope, then attenuated and split before it is recorded on two channels on a Tektronix DPO70604B digitizer. The FTD10000's ability to withstand large input voltages allows this two-scope configuration to record signal amplitudes between 1 mV and 250 Volts. A fiducial impulse signal, supplied by the NIF facility, provides a timing reference for both oscilloscopes. The cross-timing of the scope traces to the laser system is precise to within ±15 ps.

TABLE I. Error budget for pTOF-measured bang times.

Source of uncertainty	Uncertainty
Crosstiming to laser system	±15 ps
Detector IRF (in situ)	±25 ps
Forward Fit (S/N = 10)	±18 ps
Cable repeatability shot-to-shot	±5 ps
Nominal detector distance	±0.5 mm →
DT-n, DD-n, D^{3}He-p	±10 ps, 23 ps, 12 ps
On-shot alignment, typical	±1 mm →
DT-n, DD-n, D^{3}He-p	±19 ps, 46 ps, 23 ps
Magnet temporal broadening	±5 ps (D^{3}He-p only)
Mean energy:	±1 keV, 1 keV, 140 keV
DT-n, DD-n, D^{3}He-p	→ ±1 ps, 5 ps, 79 ps
Total: DT-n, DD-n, D^{3}He-p	±41 ps, 62 ps, 90 ps

II. ANALYSIS

For fusion neutrons, the source spectrum is well-approximated by a Gaussian distribution with a mean energy weakly dependent on ion temperature T_{ion} and width $\sigma \propto \sqrt{T_{ion}}$.[14] For D^{3}He protons, the spectrum will be directly measured by a WRF proton spectrometer located directly next to the pTOF diagnostic.[6] These source spectra are time-dispersed by time-of-flight to the pTOF detector to generate a source function at the detector. In addition, the burn duration of an ICF implosion adds temporal broadening to the source function; typical burn durations at the NIF are approximately 150 ps (FWHM).[15]

The source functions for nuclear particles are modeled with two independent variables: a mean time for nuclear production (bang-time), and a signal amplitude correlated to the yield. Proton and neutron source functions are scaled based on the detector sensitivity to these particles. An arbitrary source function is generated in the x-ray signal region for use in background subtraction. The source functions are combined and folded with the detector impulse response function (IRF) to generate a simulated pTOF signal, which is then fit to the measured signal using a least-squares minimization algorithm to obtain nuclear bang times and yields.

The physics of this procedure is captured in the time-of-flight equation: $t_{bang} = t_{scope} - d/\beta c$. Uncertainty in the measured particle arrival time (t_{scope}), detector distance to the implosion (d), and particle velocity (β) contribute to the overall uncertainty in the bang-time measurement. For neutrons, as the mean energy is well known, uncertainty of the inferred bang-time is dominated by uncertainty in the detector distance. For D^{3}He protons, the mean energy uncertainty as measured by WRFs, typically 140 keV, will be the dominant source of uncertainty. See Table I for a summary of uncertainties.

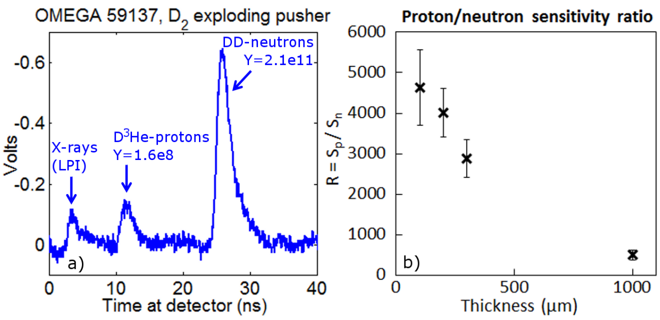

FIG. 2. pTOF calibration data recorded at OMEGA: a) DD-exploding pusher, showing signals from x-rays, DD-neutrons, and secondary D^{3}He-protons. This type of data was used to determine the pTOF sensitivity to fusion products and x-rays. b) Ratio of pTOF detector proton sensitivity to neutron sensitivity, as a function of detector thickness. Thinner detectors are observed to have higher relative proton sensitivity.

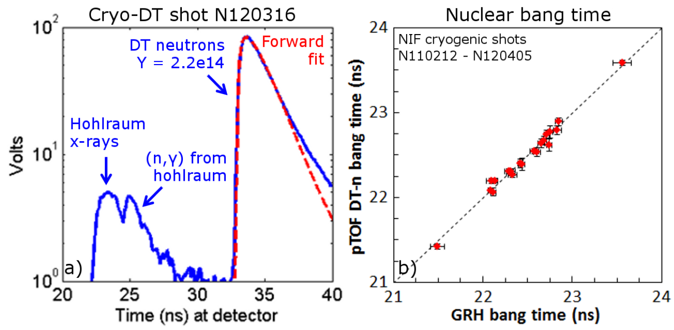

FIG. 3. pTOF data recorded at the NIF: a) Cryogenic DT shot, showing signals from x-rays, DT-neutrons, and (n,γ) reactions in the hohlraum. The best fit to the DT-neutron peak is overplotted. b) Nuclear bang-times measured with pTOF agree with measurements from GRH to within experimental uncertainties ($\chi^2_{reduced} = 0.64$).

III. CALIBRATION

The IRF of the pTOF was determined in situ on the NIF. An 88 ps FWHM laser impulse incident on a silver foil was used on several occasions to generate a short burst of x-rays that drives an impulse into the pTOF system. On x-ray impulse shot N110531, the pTOF recorded an IRF characterized by a 370 ps rise and 1.70 ns FWHM. Such shots also supply an absolute timing calibration for the pTOF system relative to the NIF laser. Uncertainty in the time-dependent spectral emission of the targets on such timing shots introduces a systematic uncertainty in the timing of the pTOF system of approximately $\pm$25ps.

pTOF detectors have been fielded at OMEGA to determine detector sensitivity to nuclear products. A typical sensitivity of 2.0×10^{-8} Volt-ns per incident 2.45-MeV-neutron and 5.4×10^{-8} Volt-ns per incident 14.1-MeV-neutron was observed in 200 μm thick diamonds at -250 Volts bias. The selection of pTOF diamonds have demonstrated a range of sensitivity by factors of 0.5 - 4 around these values. A sensitivity of 7.3×10^{-5} Volt-ns per incident 6.5 MeV proton[16] was observed for the detector at -250 Volt bias. Fig 2a) shows an example of OMEGA calibration data.

The relative sensitivity of a detector to protons and to neutrons was found to vary as a function of the detector thickness. Fig 2b) shows results from detectors between 100 and 1000 μm thick. Since x-rays and neutrons both deposit energy volumetrically in the detector, x-ray sensitivity is expected to scale with neutron sensitivity. Detectors with thickness of 200 μm were chosen to optimize proton signal relative to background.

IV. DATA

pTOF has recorded neutron data on over 70 NIF shots, including 22 cryogenic DT/THD shots, 7 DT exploding pushers, and 35 D^{3}He gas-filled surrogate shots. An example of pTOF data from a recent cryogenic DT-layered shot is shown in Fig 3a). The pTOF-measured DT-neutron bang times agree with the nuclear bang-time measured by the Gamma Reaction History diagnostic (GRH),[15] given the uncertainties involved. Fig 3b) shows pTOF vs GRH-measured nuclear bang-times.

Bang-times measured with DD-neutrons on D^{3}He surrogate shots are also in agreement with x-ray bang-time measurements; however the x-ray backgrounds have been sufficiently large to reduce the accuracy of that measurement to $\sim\pm$200 ps. Recently, 2 cm W filtering has been fielded which reduces the x-ray signal to the same order as DD-neutron signals, allowing accurate bang-time measurements.

V. CONCLUSIONS

A novel diagnostic for measuring shock and compression bang-times has been calibrated at OMEGA and designed and implemented at the NIF. The pTOF diagnostic has been absolutely timed and reports absolute bang-times using DT-neutrons and DD-neutrons. Initial data support the ongoing design of the magnet-based pTOF, for which expected signals on D^{3}He surrogate shots are $\sim$200 mV for D^{3}He-protons, $\sim$100 mV for DD-neutrons, and less than 500 mV from x-rays. This instrument will provide the first simultaneous and robust measurements of shock- and compression-bang time on surrogate D^{3}He-filled implosions at the NIF.

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