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A direct-drive exploding-pusher implosion as the first step in development of a monoenergetic charged-particle backlighting platform at the National Ignition Facility

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A B S T R A C T

A thin-glass-shell, D^3He-filled exploding-pusher inertial confinement fusion implosion at the National Ignition Facility (NIF) has been demonstrated as a proton source that serves as a promising first step toward development of a monoenergetic proton, alpha, and triton backlighting platform at the NIF. Among the key measurements, the D^3He-proton emission on this experiment (shot N121128) has been well-characterized spectrally, temporally, and in terms of emission isotropy, revealing a highly monoenergetic ($\Delta E/E \sim 4\%$) and isotropic source (~3% proton fluence variation and ~0.5% proton energy variation). On a similar shot (N130129, with D_2 fill), the DD-proton spectrum has been obtained as well, illustrating that monoenergetic protons of multiple energies may be utilized in a single experiment. These results, and experiments on OMEGA, point toward future steps in the development of a precision, monoenergetic proton, alpha, and triton source that can readily be implemented at the NIF for backlighting a broad range of high energy density physics (HEDP) experiments in which fields and flows are manifest, and also utilized for studies of stopping power in warm dense matter and in classical plasmas.

1. Introduction

The proton radiography technique [1,2] is a powerful tool in high-energy-density physics (HEDP) [3] research, providing precise images of electric and magnetic fields [4–10], as well as mass structures, in laser-generated plasma experiments. Two widely-used techniques for backlighter proton generation are the target normal sheath acceleration (TNSA) mechanism [11,12], in which a high-intensity laser irradiates a solid foil to accelerate protons, and monoenergetic charged-particle radiography [13,14], which uses fusion products

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from D^3He-filled "exploding pusher" inertial confinement fusion (ICF) implosions. The TNSA source offers excellent spatial (~10–20 μm) and temporal (~1–10 ps) resolution based on the properties of the backlighter laser, and generates a continuous spectrum of protons. The monoenergetic backlighting technique is particularly valuable in that it produces particles of a well-defined energy ($\Delta E/E$~2–5%) and superior uniformity of proton, alpha, and triton emission, enabling highly quantitative measurements. Additionally, the use of particles at different discrete energies allows for discrimination between electric and magnetic field effects and for studies of stopping power using the energy downshift of charged-particle spectra.

Monoenergetic charged-particle backlighting has been implemented and used extensively at the OMEGA laser facility [15]. This technique has provided quantitative information about fields produced in laser–foil interactions [16,17], magnetic reconnection [18,19], the Weibel instability [20], direct-drive ICF implosions [21–23], and indirect-drive ICF hohlraums [24,25]. In addition, this monoenergetic proton source has been used in experiments at OMEGA to study stopping power in warm dense matter (WDM) [26]. Though the monoenergetic charged-particle backlighting platform is well-established at OMEGA, it is only beginning to be implemented at the National Ignition Facility (NIF) [27], where a significantly greater laser energy, laser power, and spatial scale enables new regimes of HEDP experiments.

Presented here are results from a directly-driven D^3He-filled, thin-glass-shell exploding pusher implosion (shot N121128) [28], which serves as a promising first step toward the development of a baseline implosion design for monoenergetic charged-particle backlighting at the NIF. This experiment represents the first demonstration at the NIF of a monoenergetic proton source. Though this shot was conducted for diagnostic development and calibration, valuable ride-along data have been obtained, showing that this implosion serves as a useful guidepost for implementation of a monoenergetic charged-particle backlighting platform. The remainder of this paper is organized as follows: Section 2 describes the experimental setup and principal measurements that characterize this implosion and its utility as a monoenergetic proton source; and Section 3 discusses the next steps required in the implementation and usage of a monoenergetic charged-particle backlighting platform at the NIF.

2. Experimental setup and results

NIF exploding-pusher shot N121128 used a 1682-μm diameter, 2.2 g/cm³ SiO_2 shell with a wall thickness of 4.3 μm, filled with 9.1 atm of D^3He gas (3.3 atm D_2 and 5.8 atm ^3He). The capsule was coated with 0.03 μm Al to reduce the leak rate of ^3He out of the capsule.[5] The capsule was irradiated by 192 NIF beams in the polar-direct-drive (PDD) configuration [29], delivering 43.4 kJ of laser energy in a 1.4-ns ramp pulse. The laser pulse and capsule properties are illustrated in Fig. 1 and summarized, along with the principal experimental measurements, in Table 1.

This implosion produced copious DD and D^3He fusion reactions:

$$D + D \rightarrow {}^3He(0.82\,MeV) + n(2.45\,MeV), \quad (1)$$

$$D + D \rightarrow T(1.01\,MeV) + p(3.02\,MeV), \text{ and} \quad (2)$$

$$D + {}^3He \rightarrow \alpha(3.6\,MeV) + p(14.7\,MeV). \quad (3)$$

[5] The fill was intended to be 3.3 atm D_2 and 6.7 atm ^3He for an equimolar mixture, but 0.9 atm of ^3He leaked out of the capsule in the 15 hours it was removed from the pressure vessel before it was shot, based on a leak rate half-life of 76 hours.

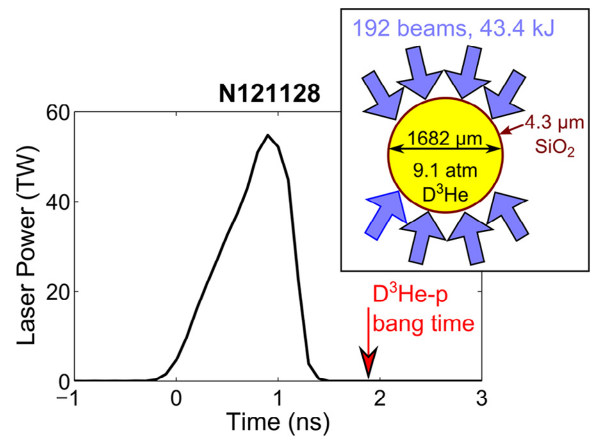

Fig. 1. (Color online) Experimental laser power history and capsule and laser parameters (inset) from NIF D^3He exploding pusher shot N121128. The time of peak D^3He-proton emission (bang time) at $t = 1.88$ ns, several hundred ps after the end of the laser pulse (~1.4 ns), is shown (see Fig. 2 for the raw proton bang time data).

The monoenergetic particle backlighting platform will be designed to utilize the D^3He protons and alphas (Equation 3) as well as the DD protons and tritons (Equation 2). Shot N121128 was diagnosed through measurements of DD-neutron (Equation 1) emission using the neutron time-of-flight (nTOF) suite [30] and primarily through measurements of D^3He-proton emission using wedge range filter (WRF) proton spectrometers [31–33] and the particle time-of-flight (pTOF) diagnostic [34]. As has been described in detail elsewhere [28], the nTOF-measured DD-neutron yield was 7.27×10^{10} (and based on the DD-n/DD-p branching ratio of ~0.98 at the measured DD-burn-averaged ion temperature of 7.1 keV, the DD-proton yield is expected to have been 7.4×10^{10}); the WRF-measured D^3He-proton yield was 2.09×10^{10}. Uncertainty in the DD-n yield measurement was ~ ±10%, while uncertainty in the D^3He-p yield measurement was around ±3% based on excellent spatial uniformity of the inferred proton yields. Yields of this magnitude are more than sufficient for charged-particle backlighting experiments at the NIF, where ideal particle fluences of ~10^5 cm^{-2} would be achieved at CR-39 [35,36] detectors positioned 50–200 cm from the experiments. Burn-averaged ion temperatures inferred from the Doppler width of the fusion-product spectra were inferred to be 7.1 ± 0.5 keV averaged over the DD-n reactions (measured by nTOFs) and 11.0 ± 2.0 keV averaged over the D^3He reactions (measured by WRFs) [28].[6] The difference between DD-burn-averaged and D^3He-burn-averaged ion temperatures is likely a consequence of the difference in temperature dependence of the fusion reactivity of reactions 1 and 3, with DD (D^3He) reactions weighted more strongly to the cooler (hotter) regions of the fuel. Thermal decoupling of ^3He and deuterium ions (with ^3He ions hotter due to stronger heating by the shock) [37] is another possible contributing factor. Using an independent measurement technique based on the ratio of DD and D^3He yields [38], the ion temperature was inferred to be 6.9 ± 1.0 keV, in reasonable agreement with the linewidth-inferred ion temperature. The total ρR was inferred from the downshift of the D^3He-p spectrum to be 9 ± 4 mg/cm². The time of peak D^3He-p emission (bang time) was measured by pTOF to be 1.88 ± 0.10 ns, several hundred ps after the end of the laser pulse [28]. The pTOF trace obtained on shot N121128, originally presented in Ref. [28], is shown in Fig. 2, illustrating a robust D^3He-p signal and minimal x-ray background.

[6] These measurements assume that the width of the neutron and proton spectra are due entirely to thermal broadening and not to flows.