

LETTER | MAY 05 2026

Fusion alpha particle momentum deposition in thermonuclear burn dynamics

A. J. Crilly ; B. D. Appelbe ; E. A. Ferdinandi ; S. T. O'Neill ; H. M. Biragnet ; N. Chaturvedi ; J. P. Chittenden ; B. Duhig ; P. W. Moloney 



Phys. Plasmas 33, 050702 (2026)

<https://doi.org/10.1063/5.0327431>



Articles You May Be Interested In

Gain curves for direct-drive fast ignition at densities around 300 g/cc

Phys. Plasmas (October 2006)

High-density carbon ablator ignition path with low-density gas-filled rugby hohlraum

Phys. Plasmas (April 2015)

Saturation levels of neoclassical tearing modes in International Thermonuclear Experimental Reactor plasmas

Phys. Plasmas (August 2005)



Physics of Plasmas

Special Topics Open
for Submissions

[Learn More](#)



Fusion alpha particle momentum deposition in thermonuclear burn dynamics

Cite as: Phys. Plasmas **33**, 050702 (2026); doi: [10.1063/5.0327431](https://doi.org/10.1063/5.0327431)

Submitted: 11 February 2026 · Accepted: 12 April 2026 ·

Published Online: 5 May 2026



View Online



Export Citation



CrossMark

A. J. Crilly,^{1,2,a)} B. D. Appelbe,¹ E. A. Ferdinandi,¹ S. T. O'Neill,³ H. M. Biragnet,¹ N. Chaturvedi,¹
J. P. Chittenden,¹ B. Duhig,¹ and P. W. Moloney¹

AFFILIATIONS

¹Centre for Inertial Fusion Studies, The Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom

²I-X Centre for AI In Science, Imperial College London, White City Campus, 84 Wood Lane, London W12 0BZ, United Kingdom

³York Plasma Institute, School of Physics, Engineering and Technology, University of York, Heslington, York YO10 5DD, United Kingdom

^{a)}Author to whom correspondence should be addressed: ac116@ic.ac.uk

ABSTRACT

In inertial confinement fusion, the deuterium and tritium fusion alpha particles carry not only energy but also appreciable momentum that is typically neglected in models of thermonuclear burn. In the central hotspot ignition scheme, the hotspot must self-heat and propagate thermonuclear burn before disassembly. Using radiation-hydrodynamics simulations with a Monte Carlo alpha particle transport model, we investigate the effect of alpha momentum deposition across sub-ignition to robustly igniting regimes by hydrodynamic scaling of current central hotspot ignition designs from the National Ignition Facility (NIF). We find that the effective alpha particle ram pressure accelerates the shell at burn, reducing hotspot compression, increasing the rate of disassembly and decreasing yield. This causes a notable (~30%) reduction in yield at current NIF scale, with a persistent (~10%) penalty at larger hydrodynamic scales. These results demonstrate that alpha momentum deposition is a significant effect for present ignition-scale implosions, necessitating its inclusion in ignition criteria, burn models, and designs for high-gain inertial confinement fusion.

© 2026 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/5.0327431>

Inertial confinement fusion (ICF) experiments involve the compression of fusion fuel, deuterium and tritium (DT), to high densities and temperatures to achieve thermonuclear burn.¹ In the central hotspot ignition scheme, a hot, lower density hotspot surrounded by a cold, higher density shell is assembled by implosion. Thermonuclear burn is initiated in the hotspot, and the fusion of DT releases alpha particles which deposit their energy back into the fuel. With sufficient fusion self-heating, the hotspot can “ignite” and propagate a fusion burn wave into the cold shell.^{2–7} In this manner, ICF implosions can achieve net energy gain from fusion. Ignition and energy gain with the central hotspot ignition scheme has been achieved experimentally at the National Ignition Facility.^{8–10} For these experiments, fusion particle heating dominates the power balance⁷ and therefore a detailed understanding of the coupling of the fusion products to the fuel is paramount.

Alpha particle energy deposition is the key physical process in thermonuclear burn and has been thoroughly studied in theory, simulation, and current ignition experiments. However, the fast fusion

alphas (born with 3.5 MeV of kinetic energy) also carry significant momentum,¹¹ the effect of which is usually overlooked. In this letter, we show that alpha momentum deposition has a significant deleterious effect on yield for current central hotspot ignition designs. We quantify the effect using detailed alpha transport calculations within radiation hydrodynamics simulations. We show that the largest effect on performance occurs at current NIF experimental scale and the effect is reduced, but persistent, for hydrodynamically scaled implosions.

The introduction of alpha momentum deposition ($S_{\rho v}$) acts as a source within the momentum equation of hydrodynamics

$$\frac{\partial \rho v}{\partial t} + \nabla(P + \rho v^2) = S_{\rho v}. \quad (1)$$

During the stagnation phase of ICF, the flow is subsonic¹² and therefore alpha momentum deposition causes the hotspot and shell to depart from isobaricity. The effective ram pressure of the alphas acts to increase the shell thermal pressure relative to the hotspot pressure.

Approximating the alpha momentum deposition term, one can find the shell-hotspot pressure ratio by integrating over the hotspot-shell boundary region¹³ (Ω_b):

$$\int_{\Omega_b} \nabla P d^3r \approx 4\pi R_{HS}^2 (P_{shell} - P_{HS}), \quad (2)$$

$$\int_{\Omega_b} S_{\rho v} d^3r \approx f_{\rho v} m_\alpha v_\alpha dY/dt, \quad (3)$$

$$\frac{P_{shell}}{P_{HS}} - 1 \approx f_{\rho v} \frac{m_\alpha v_\alpha dY/dt}{4\pi P_{HS} R_{HS}^2} \equiv f_{\rho v} \beta, \quad (4)$$

where P denotes the pressure, R the radius, dY/dt the total rate of alpha production, and m_α and v_α the mass and velocity of DT fusion alpha particles, and we define β as the alpha momentum-to-thermal force ratio and $f_{\rho v}$ to be the fraction of total alpha momentum coupled to radial fluid momentum, which is equal to $2/3$ in the uniform, free-streaming limit.¹⁴ The alpha-induced increased pressure gradient across the shell will act to accelerate the shell radially outwards. Radial acceleration of the shell will result in reduced hotspot compression and therefore reduced hotspot pressure.

To compensate for lost compression created by the alpha momentum deposition, the implosion will require additional kinetic energy to achieve ignition conditions. This prompts us to revisit the implosion velocity requirement for ignition and include the effect of alpha particle momentum. Betti *et al.*¹² derive a hotspot ignition requirement on shell kinetic energy using a compressible shell model. This includes the effects of alpha heating but not momentum deposition. Here, we add the increase in required shell kinetic energy to perform work against the effective alpha ram pressure:

$$\frac{1}{2} M_{shell} v_{imp}^2 = \int P_{shell} dV, \quad (5a)$$

$$\frac{1}{2} M_{shell} (v_{noz\rho v}^{ign} + \Delta v_{\alpha\rho v}^{ign})^2 = \int (1 + f_{\rho v} \beta) P_{HS} dV, \quad (5b)$$

$$\Delta v_{\alpha\rho v}^{ign} \approx \frac{1}{2} \langle f_{\rho v} \beta \rangle_{PdV} \cdot v_{noz\rho v}^{ign},$$

$$v_{noz\rho v}^{ign} = 310 \text{ km/s} \left[\alpha_{if}^{2.4} \left(\frac{1 \text{ mg}}{M_{shell}} \right) \left(\frac{100 \text{ MBar}}{P_a} \right)^{0.39} \right]^{\frac{1}{7}}, \quad (5c)$$

where the no-alpha momentum ignition criterion is taken from Betti *et al.*,¹² v_{imp} is the implosion velocity, α_{if} is the in-flight adiabat,^{12,15} M_{shell} is the mass of the shell, and P_a is the peak ablation pressure. We have assumed small alpha momentum-to-thermal force ratio ($f_{\rho v} \beta$), corresponding to a marginal ignition scenario. Furthermore, by using Eq. (4), we find

$$\Delta v_{\alpha\rho v}^{ign} = \frac{1}{2} \frac{\int f_{\rho v} \beta P dV}{\int P dV} v_{noz\rho v}^{ign} \approx \Delta v_{shell} \cdot \nu, \quad (6a)$$

$$\Delta v_{shell} \equiv \frac{f_{\rho v} Y_\alpha^{ign} m_\alpha v_\alpha}{M_{shell}}, \quad \nu \equiv \frac{\int_0^{Y_\alpha^{ign}} v dY}{v_{noz\rho v}^{ign} Y_\alpha^{ign}}, \quad (6b)$$

where Δv_{shell} is the total change in shell velocity due to alpha momentum and ν is an efficiency term related to the loss of PdV work due to

alpha momentum. If we use the ignition yield (Y_α^{ign}) definition as in Herrmann, Tabak and Lindl¹⁵ (fusion energy equal to absorbed capsule energy), we arrive at a final quantitative estimate,

$$\Delta v_{\alpha\rho v}^{ign} = 33 \text{ km/s} \nu \left(\frac{f_{\rho v}}{2/3} \right) \left(\frac{v_{imp}}{400 \text{ km/s}} \right)^2 \left(\frac{0.05}{\eta_{hydro}} \right), \quad (7)$$

where η_{hydro} is the hydrodynamic efficiency.¹⁶ Therefore, we see that the implosion velocity required for ignition is increased by alpha momentum, leading to an effective shift of the “ignition cliff,” where the yield is maximally sensitive to implosion parameters.

In the following we will quantify the effect of alpha momentum on current ignition designs, as well as hydrodynamically scaled versions. Hydrodynamic scaling involves uniformly scaling space and time by a factor S to maintain dynamical similarity. Although additional physical processes break pure scaling, hydrodynamically equivalent implosions can be achieved through systematic re-tuning of target (e.g., radii and thicknesses) and drive (e.g., duration) parameters about the pure S scaling.¹⁷ We use as our baseline the NIF shot N210808,⁸ the first ICF experiment to exceed Lawson’s criterion for ignition.¹⁸ The N210808 design has a peak implosion velocity of ~ 400 km/s as well as a $v_{noz\rho v}^{ign} \sim 400$ km/s. It therefore sits on the ignition cliff. Equation 7 suggests up to a few 10s km/s increase in the ignition threshold—this will result in a large change in yield. Considering hydrodynamic equivalent¹⁷ implosions, one finds the implosion velocity required for ignition decreases as $v_{imp}^{ign} \propto S^{-3/7}$. Therefore, larger scales will robustly ignite even in the presence of alpha momentum. However, the energy gain will be reduced as alpha momentum deposition will speed up the rarefaction of the burning fuel. To investigate the effects of alpha momentum in different regimes, we simulated hydrodynamic scales, S , from 0.75 to 2.0 ($S \sim E_{driver}^{1/3}$ and therefore equivalent to laser driver energies of 0.8 to 15.2 MJ) to span the sub-ignition to robustly igniting regimes of central hotspot ignition, where we take N210808 as scale 1.

Spherical 1D radiation hydrodynamics simulations were performed with the Eulerian radiation magnetohydrodynamics code Chimera, with 250 nm radial resolution during burn. Chimera has a Monte Carlo alpha heating model,^{19,20} details of ICF implosion modeling with Chimera can be found in the literature.^{19,21–27} The as-shot capsule dimensions were used in combination with a frequency-dependent spectrum radiation drive (calculated from integrated hohlraum simulations with HYDRA²⁸) and a surrogate Germanium dopant with increased dopant fraction (tuning found $\sim 4\times$ required²⁶) as compared to the experimentally used tungsten. A re-tuning of the 210808 design was performed at each new scale factor to ensure hydrodynamic equivalent¹⁷ implosions. This was performed automatically by a Bayesian optimization framework,²⁹ aiming to preserve the scale = 1 implosion trajectory parameters [$v_{shell}(t)$, scaled burn-off bang time, and scaled ρR] across all scales by varying the doped and outer undoped ablator thicknesses.

To quantify the isolated effect of alpha momentum deposition, the Monte Carlo alpha heating model¹⁹ was run in two modes. First, an alpha energy transport only mode in which alpha particles deposit their energy only and helium ash is locally deposited, giving rise to fuel depletion effects. Second, the full alpha transport mode which includes the mass, momentum, and energy transport effects. More

explicitly, the coupling of alpha particle transport to the fluid involves the following updates to hydrodynamic quantities over a time step:

$$\Delta\rho = m_\alpha n_{\text{thermalise}} - (m_D + m_T)n_{\text{spawn}}, \quad (8a)$$

$$\Delta U_i = \frac{\sum f_i \Delta E}{V_{\text{cell}}} - \langle E \rangle_{DT} n_{\text{spawn}}, \quad (8b)$$

$$\Delta U_e = \frac{\sum (1 - f_i) \Delta E}{V_{\text{cell}}}, \quad (8c)$$

$$\Delta\rho v = \frac{m_\alpha \sum \Delta v}{V_{\text{cell}}} - (m_D + m_T) v n_{\text{spawn}}, \quad (8d)$$

where n_i is the number density of population i , ΔE and Δv are the changes in particle energy and velocity from particle–fluid interactions, f_i is the fraction of energy deposited going to the ions, $\langle E \rangle_{DT}$ is the DT Gamow energy,³⁰ and summations run over all computational particles in the cell (of volume V_{cell}). The particle energy and velocity changes are computed using both deterministic friction and stochastic diffusion terms, as in Tong *et al.*¹⁹ and Sherlock.²⁰ The stopping power model is Zimmerman's implementation of Maynard–Deutsch³¹ and the thermalization energy cut off is 10 keV, after which thermalized alpha particle density is counted in $n_{\text{thermalise}}$. The full transport model includes all terms as above. The alpha energy only transport model has $\Delta\rho v = 0$ and $\Delta\rho = (m_\alpha - m_D - m_T)n_{\text{spawn}}$ for local helium ash generation.

The scaled radiation hydrodynamics simulations showed that alpha momentum deposition has a significant effect ($\geq 10\%$) on fusion yield for all ignited implosions ($Y_{\text{amp}} > 10$), as shown in Fig. 1. The largest effect was seen at the current NIF scale, where the yield was reduced by $\sim 30\%$ when the full alpha particle transport model was used. The fusion yields for alpha energy only and full alpha transport models were 4.2 and 2.9 MJ, respectively, compared to the 1.37 MJ achieved in the N210808 experiment.^{9,10} The scaled designs plateau in yield amplification at ~ 300 and ~ 260 for alpha energy only and full alpha transport models, respectively. The effect of alpha momentum shows a similar plateau at a $\sim 10\%$ reduction in yield.

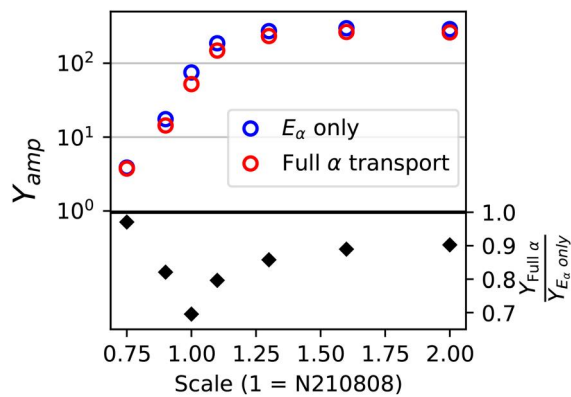


FIG. 1. (Top) The yield amplification (ratio of simulated yields with and without alpha heating) from different hydrodynamic scales. Yield amplification is used to factor out the (no alpha heating) yield changes purely from increased scale. Scale = 1 represents current designs at the NIF (in this work, N210808). Shown in blue and red symbols are calculations from Chimera. (Bottom) The ratio of yields from full alpha particle transport to alpha energy transport only.

The effect of alpha momentum deposition is quantified by the dimensionless force ratio, β , as defined in Eq. (4). This ratio quantifies the relative importance of alpha momentum and thermal pressure on the shell acceleration. As shown in Fig. 2, β is of order 0.1–1.0 for scales considered in this study. We calculate the alpha momentum coupling efficiency from simulation and we find that $f_{\rho v}$ varies between 0.60 and 0.66. The magnitude of the alpha momentum-to-thermal force ratio and momentum coupling efficiency show that alpha momentum will have a notable effect on stagnation and disassembly of the fuel. However, simulations show that a larger β value does not equate to a larger reduction in yield. As the hotspot is igniting, hotspot confinement is crucial to allowing self-heating. Premature hotspot decompression can quench ignition.⁵ However, once ignited, burn occurs until the fuel rarefies. This rarefaction occurs at approximately the sound speed^{32,33} but will be accelerated by the alpha momentum. This leads to an additional difficulty in achieving high burn-up fractions in the presence of alpha momentum-driven rarefaction, as shown in Fig. 1.

Alpha momentum deposition will also drive pressure gradients where it is peaked. This is typically at the hotspot edge due to a combination of a geometric effect (the alpha momentum flux is zero by symmetry at the origin) and the rapid decrease in stopping distance at the hotspot edge. We therefore expect to see an increase in radial pressure gradient in the presence of alpha momentum. By finding the time of peak momentum deposition at the hotspot edge, we aim to quantify this effect by finding the difference in the pressure gradient between our two alpha transport model scenarios. As shown in the middle plot of Fig. 2, this pressure gradient effect is reflected in the integrated simulations, with increasingly larger positive pressure gradients driven at the peak of momentum deposition. At the larger scales, the change in pressure gradient diverges from the alpha momentum driving force term. However, for these large scales, the increased alpha heating in the alpha energy only simulations drives a positive pressure gradient at the hotspot edge. This is because the hotspot becomes transparent and energy deposition becomes peaked at the hotspot edge. For MJ level fusion yields, a simple momentum transfer estimate suggests that fusion alpha particles will add 10s km/s of radial velocity to the disassembling fuel. As shown in the right-hand side plot of Fig. 2, the shell velocity is increased by ~ 30 km/s at the time of peak alpha momentum deposition for scale 1, relative to the alpha energy transport only simulation. This is also the time of peak β , and therefore the time at which we expect the largest effect from alpha momentum on the shell dynamics.

During the onset of ignition at scale 1, the reduced compression during burn caused by the effective alpha particle ram pressure shortens the time for which the hotspot is self-heating. This can be seen by comparing trajectories in $\rho R_{\text{HS}} - \langle T_i \rangle$ space^{16,32} with and without alpha momentum deposition effects, as shown in Fig. 3. The reduction in shell velocity, leads to a reduction in hotspot pressure and areal density. The $\rho R_{\text{HS}} - \langle T_i \rangle$ trajectory is therefore shifted to lower areal density, entering the ignition region later and therefore with less confinement. At the time when 10% of the yield has been produced, alpha ram pressure has reduced the hotspot areal density by 50 mg/cm². Without this effect, the hotspot is on the point of ignition, by Atzeni's metric.³² As the burn continues, the trajectories diverge considerably, seeded by the ~ 30 km/s reduction in shell velocity. Key measurable quantities reflect the changes in these burn trajectories. Comparing

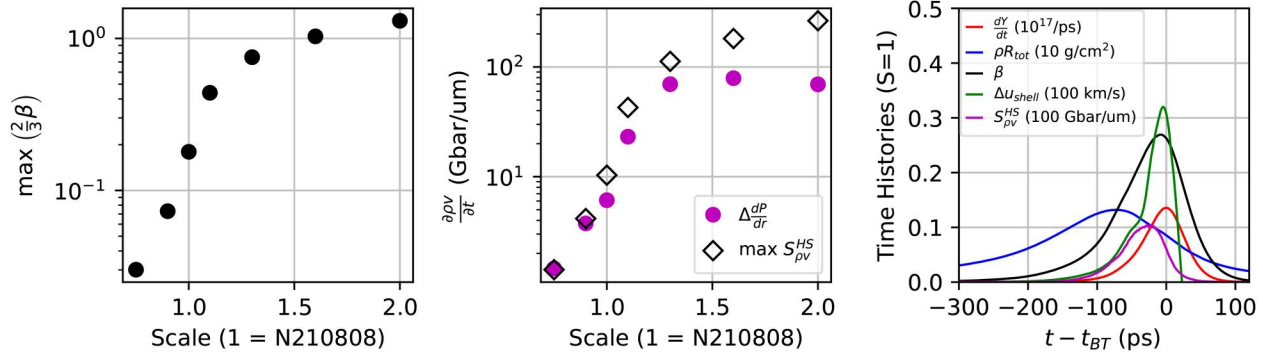


FIG. 2. (Left) The maximal value of the alpha momentum-to-thermal force ratio, β , as a function of hydrodynamic scale. (Middle) The alpha momentum-driven pressure gradients and peak alpha momentum deposition rate as a function of scale; given in units of Gbar/ μm , i.e., rates of change of momentum density ($\partial\rho v/\partial t$). The alpha momentum-driven pressure gradients, $\Delta P/dr$, are found by taking the difference between simulations with and without alpha momentum transport. The pressure gradients and alpha momentum deposition rates are calculated at the hotspot radius (defined as the radius enclosing 98% of neutron production). (Right) Time series from the scale = 1 calculation with the full alpha transport model, where t_{BT} is the nuclear bang time. The change in shell velocity Δu_{shell} is calculated by taking the difference between fuel areal density averaged velocities from simulations with and without alpha momentum transport.

energy only and full alpha transport and experiment,^{9,10} respectively, the reduced compression leads to reduced total ($0.60/0.57/0.54 \pm 0.05 \text{ g/cm}^2$) and hotspot ($0.48 / 0.41/0.44 \pm 0.05 \text{ g/cm}^2$) fuel areal densities as well as a reduction in the apparent DT ($13.9/12.1/10.9 \pm 0.4 \text{ keV}$) and DD ($13.3/11.6/8.94 \pm 0.4 \text{ keV}$) ion temperatures.

Inspecting scale 1, hydrodynamic profiles at the time by which 10 % of yield has been produced in Fig. 4 show the spatial dependence of the alpha transport effects, and the same trends discussed below continue throughout the burn. The most notable difference is in the pressure profile. The effect of alpha momentum deposition is a reduction in hotspot pressure and a relative increase in shell pressure. In particular, a positive pressure gradient is established at the hotspot edge. The alpha momentum deposition is also strongly peaked at the hotspot edge, as discussed above. The positive fluid velocity (radial expansion) is increased across hotspot and shell, apart from at the hotspot edge. At the hotspot edge, the positive pressure gradient acts to decelerate the flow, in line with the expected change to the ablation process.³⁴ Both the reduced hotspot compression and the alpha mass

transport effect lead to reduced hotspot density and increased shell density, shown by the ratio of density between the α -transport models in the bottom subplot of Fig. 4. At this time, the effect on temperature is at the few percent level; therefore, the majority of the pressure reduction is reflected in the mass density reduction. For the center of

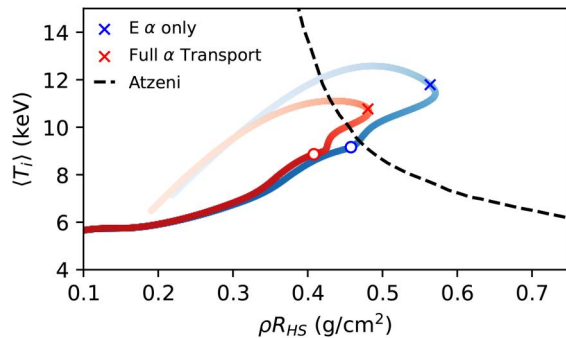


FIG. 3. Trajectories in $\rho_{\text{RHS}} - \langle T_i \rangle$ space from scale = 1 calculations; full alpha transport in red and energy only in blue. The opacity of the points are colored by the fraction of burn. Conditions at the time of peak neutron production are shown with crosses and at 10% of total yield with empty circles. Also shown, as a black dashed line, is the ignition boundary as given in Atzeni and Meyer-ter Vehn.³²

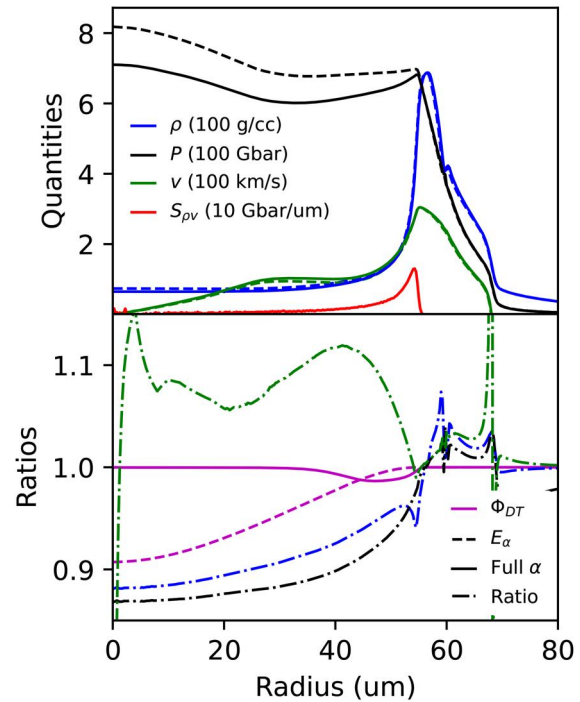


FIG. 4. Radial profiles of mass density (ρ), pressure (P), velocity (v), and momentum deposition rate (S_{pv}), and local unburnt DT fraction (Φ_{DT}) for the energy only and full alpha transport models, at 10% of total yield—energy-only and full α transport shown in dashed and full lines, respectively. In the lower plot, shown in the dot-dashed lines, are ratios of the hydrodynamic quantities where the ratio is (full alpha transport result)/(energy only transport result).

the hotspot, a significant fraction of the density reduction is due to mass transport, i.e., non local helium ash deposition. This is shown as the center of the hotspot, which is only 90% unburnt DT fuel for local mass deposition. However, across the whole hotspot, the unburnt DT mass density is reduced in the full transport model, showing that the loss of hotspot areal density is driven predominantly by alpha momentum-driven decompression.

In conclusion, we show that alpha momentum deposition has a significant effect on burn dynamics in the central hotspot ignition scheme. In particular, we show the largest sensitivity ($\sim 30\%$ reduction in yield) on the ignition cliff, where current ICF experiments at the NIF are operating. The alpha momentum acts as effective additional ram pressure which radially accelerates the shell. The increased acceleration results in reduced compression during burn and therefore a loss in fusion yield. This effect is not usually accounted for in theoretical models of ignition and burn.^{2,7,13,35} Indeed, a limited number of studies^{36–38} carried out, before the National Ignition Facility was built, for early central hotspot ignition designs, appear to have been neglected by the community. Without modeling of the deleterious effect of alpha momentum, reduced performance and compression in the experiment would likely be attributed to other poorly constrained degradation mechanisms such as fuel preheating, shock mis-timing, and fuel–ablator mix.³⁹ Direct experimental validation of the alpha momentum effect will likely be difficult due to the degeneracy with other degradation mechanisms. Indeed, the magnitude of the shell velocity change from alpha momentum (few 10s km/s) is similar to that of the residual kinetic energy⁴⁰ in current experiments. Additionally, momentum deposition (and mass transport) effects are more difficult to include in alpha energy diffusion models^{41,42} (which are commonplace in ICF simulation codes^{43–46}) compared to particle-based methods¹⁹—we note that in HYDRA, momentum deposition is accounted for all the transported particles.²⁸ In this work, we consider the 1D effect of alpha momentum for central hotspot ignition; however, this prompts further investigation into effects on hydrodynamic instability growth in burn,³⁸ the creation of alpha-induced electrical currents^{47,48} and other ignition schemes.^{49–51} Looking forward to high-gain ICF, the dominant role of fusion products in both energetics and dynamics demands models which include the full complexity of thermonuclear burn.

ACKNOWLEDGMENTS

This research received support through Schmidt Sciences, LLC and the Imperial College Research Fellowship program. This work made use of the Imperial College London RCS High Performance Computing systems.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

A. J. Crilly: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Funding acquisition (lead); Investigation (lead); Methodology (lead); Software (equal); Visualization (lead); Writing – original draft (lead). **B. D. Appelbe:** Conceptualization (equal);

Formal analysis (equal); Investigation (equal); Writing – review & editing (equal). **E. A. Ferdinandi:** Methodology (equal); Software (equal). **S. T. O'Neill:** Conceptualization (equal); Formal analysis (equal); Investigation (equal). **H. M. Biragnet:** Conceptualization (equal); Software (equal). **N. Chaturvedi:** Conceptualization (equal); Software (equal). **J. P. Chittenden:** Conceptualization (equal); Project administration (equal); Resources (equal); Software (equal). **B. Duhig:** Conceptualization (equal); Software (equal). **P. W. Moloney:** Conceptualization (equal); Software (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, "Laser compression of matter to super-high densities: Thermonuclear (CTR) applications," *Nature* **239**(5368), 139–142 (1972).
- A. R. Christopherson, R. Betti, A. Bose, J. Howard, K. M. Woo, E. M. Campbell, J. Sanz, and B. K. Spears, "A comprehensive alpha-heating model for inertial confinement fusion," *Phys. Plasmas* **25**(1), 012703 (2018).
- A. R. Christopherson, R. Betti, S. Miller, V. Gopalaswamy, O. M. Mannion, and D. Cao, "Theory of ignition and burn propagation in inertial fusion implosions," *Phys. Plasmas* **27**(5), 052708 (2020).
- O. A. Hurricane, D. A. Callahan, D. T. Casey, P. M. Celliers, C. Cerjan, E. L. Dewald, T. R. Dittrich, T. Döppner, D. E. Hinkel, L. F. B. Hopkins, J. L. Kline, S. Le Pape, T. Ma, A. G. MacPhee, J. L. Milovich, A. Pak, H.-S. Park, P. K. Patel, B. A. Remington, J. D. Salmonson, P. T. Springer, and R. Tommasini, "Fuel gain exceeding unity in an inertially confined fusion implosion," *Nature* **506**, 343–348 (2014).
- O. A. Hurricane, D. A. Callahan, D. T. Casey, E. L. Dewald, T. R. Dittrich, T. Döppner, S. Haan, D. E. Hinkel, L. F. Berzak Hopkins, O. Jones *et al.*, "Inertially confined fusion plasmas dominated by alpha-particle self-heating," *Nat. Phys.* **12**(8), 800–806 (2016).
- O. A. Hurricane, S. A. Maclaren, M. D. Rosen, J. H. Hammer, P. T. Springer, and R. Betti, "A thermodynamic condition for ignition and burn-propagation in cryogenic layer inertially confined fusion implosions," *Phys. Plasmas* **28**(2), 022704 (2021).
- O. A. Hurricane, D. A. Callahan, D. T. Casey, A. R. Christopherson, A. L. Kritcher, O. L. Landen, S. A. Maclaren, R. Nora, P. K. Patel, J. Ralph, D. Schlossberg, P. T. Springer, C. V. Young, and A. B. Zylstra, "Energy principles of scientific breakeven in an inertial fusion experiment," *Phys. Rev. Lett.* **132**, 065103 (2024).
- H. Abu-Shawareb, R. Acree, P. Adams, J. Adams, B. Addis, R. Aden, P. Adrian, B. B. Afeyan, M. Aggleton *et al.*, "Achievement of target gain larger than unity in an inertial fusion experiment," *Phys. Rev. Lett.* **132**, 065102 (2024).
- A. L. Kritcher, A. B. Zylstra, D. A. Callahan, O. A. Hurricane, C. R. Weber, D. S. Clark, C. V. Young, J. E. Ralph, D. T. Casey, A. Pak, O. L. Landen, B. Bachmann, K. L. Baker, L. Berzak Hopkins, S. D. Bhandarkar, J. Biener, R. M. Bionta, N. W. Birge, T. Braun, T. M. Briggs, P. M. Celliers, H. Chen, C. Choate, L. Divol, T. Döppner, D. Fittinghoff, M. J. Edwards, M. Gatu Johnson, N. Gharibyan, S. Haan, K. D. Hahn, E. Hartouni, D. E. Hinkel, D. D. Ho, M. Hohenberger, J. P. Holder, H. Huang, N. Izumi, J. Jeet, O. Jones, S. M. Kerr, S. F. Khan, H. Geppert Kleinrath, V. Geppert Kleinrath, C. Kong, K. M. Lamb, S. Le Pape, N. C. Lemos, J. D. Lindl, B. J. MacGowan, A. J. Mackinnon, A. G. MacPhee, E. V. Marley, K. Meaney, M. Millot, A. S. Moore, K. Newman, J.-M. G. Di Nicola, A. Nikroo, R. Nora, P. K. Patel, N. G. Rice, M. S. Rubery, J. Sater, D. J. Schlossberg, S. M. Sepke, K. Sequoia, S. J. Shin, M. Stadermann, S. Stoupin, D. J. Strozzi, C. A. Thomas, R. Tommasini, C. Troselle, E. R. Tubman, P. L. Volegov, C. Wild, D. T. Woods, and S. T. Yang, "Design of an inertial fusion experiment exceeding the Lawson criterion for ignition," *Phys. Rev. E* **106**, 025201 (2022).

- ¹⁰A. B. Zylstra, A. L. Kritcher, O. A. Hurricane, D. A. Callahan, J. E. Ralph, D. T. Casey, A. Pak, O. L. Landen, B. Bachmann, K. L. Baker, L. Berzak Hopkins, S. D. Bhandarkar, J. Biener, R. M. Bionta, N. W. Birge, T. Braun, T. M. Briggs, P. M. Celliers, H. Chen, C. Choate, D. S. Clark, L. Divol, T. Döppner, D. Fittinghoff, M. J. Edwards, M. Gatu Johnson, N. Gharibyan, S. Haan, K. D. Hahn, E. Hartouni, D. E. Hinkel, D. D. Ho, M. Hohenberger, J. P. Holder, H. Huang, N. Izumi, J. Jeet, O. Jones, S. M. Kerr, S. F. Khan, H. Geppert Kleinrath, V. Geppert Kleinrath, C. Kong, K. M. Lamb, S. Le Pape, N. C. Lemos, J. D. Lindl, B. J. MacGowan, A. J. Mackinnon, A. G. MacPhee, E. V. Marley, K. Meaney, M. Millot, A. S. Moore, K. Newman, J.-M. G. Di Nicola, A. Nikroo, R. Nora, P. K. Patel, N. G. Rice, M. S. Rubery, J. Sater, D. J. Schlossberg, S. M. Sepke, K. Sequoia, S. J. Shin, M. Stadermann, S. Stoupin, D. J. Strozzi, C. A. Thomas, R. Tommasini, C. Trosseille, E. R. Tubman, P. L. Volegov, C. R. Weber, C. Wild, D. T. Woods, S. T. Yang, and C. V. Young, "Experimental achievement and signatures of ignition at the National Ignition Facility," *Phys. Rev. E* **106**, 025202 (2022).
- ¹¹For a fusion yield of 1 MJ, the alpha particles carry a total momentum of 30 mg km/s. Typical ICF implosion velocities are 300–400 km/s for shell masses of tenths of mg.
- ¹²R. Betti, K. Anderson, V. N. Goncharov, R. L. McCrory, D. D. Meyerhofer, S. Skupsky, and R. P. J. Town, "Deceleration phase of inertial confinement fusion implosions," *Phys. Plasmas* **9**(5), 2277–2286 (2002).
- ¹³W. Doughton, B. J. Albright, S. M. Finnegan, B. M. Haines, J. L. Kline, J. P. Sauppe, and J. M. Smidt, "Influence of mass ablation on ignition and burn propagation in layered fusion capsules," *Phys. Plasmas* **30**(1), 012704 (2023).
- ¹⁴One can estimate the alpha momentum coupling efficiency, $f_{\alpha v}$, from a uniformly emitting, transparent, spherical hotspot model, for which one can compute $f_{\alpha v}$ from the average (weighted by surface intensity) radial component of alpha velocity at the hotspot edge ($\langle \vec{v}_\alpha \cdot \hat{r} \rangle / v_\alpha$) which is equal to 2/3.
- ¹⁵M. C. Herrmann, M. Tabak, and J. D. Lindl, "A generalized scaling law for the ignition energy of inertial confinement fusion capsules," *Nucl. Fusion* **41**(1), 99 (2001).
- ¹⁶J. Lindl, "Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain," *Phys. plasmas* **2**(11), 3933–4024 (1995).
- ¹⁷R. Nora, R. Betti, K. S. Anderson, A. Shvydky, A. Bose, K. M. Woo, A. R. Christopherson, J. A. Marozas, T. J. B. Collins, P. B. Radha, S. X. Hu, R. Epstein, F. J. Marshall, R. L. McCrory, T. C. Sangster, and D. D. Meyerhofer, "Theory of hydro-equivalent ignition for inertial fusion and its applications to OMEGA and the National Ignition Facility," *Phys. Plasmas* **21**(5), 056316 (2014).
- ¹⁸S. E. Wurzel and S. C. Hsu, "Progress toward fusion energy breakeven and gain as measured against the Lawson criterion," *Phys. Plasmas* **29**(6), 062103 (2022).
- ¹⁹J. K. Tong, K. McGlinchey, B. D. Appelbe, C. A. Walsh, A. J. Crilly, and J. P. Chittenden, "Burn regimes in the hydrodynamic scaling of perturbed inertial confinement fusion hotspots," *Nucl. Fusion* **59**(8), 086015 (jun 2019).
- ²⁰M. Sherlock, "A Monte-Carlo method for coulomb collisions in hybrid plasma models," *J. Comput. Phys.* **227**(4), 2286–2292 (2008).
- ²¹J. P. Chittenden, B. D. Appelbe, F. Manke, K. McGlinchey, and N. P. L. Niasse, "Signatures of asymmetry in neutron spectra and images predicted by three-dimensional radiation hydrodynamics simulations of indirect drive implosions," *Phys. Plasmas* **23**(5), 052708 (2016).
- ²²C. A. Walsh, J. P. Chittenden, K. McGlinchey, N. P. L. Niasse, and B. D. Appelbe, "Self-generated magnetic fields in the stagnation phase of indirect-drive implosions on the National Ignition Facility," *Phys. Rev. Lett.* **118**(15), 155001 (2017).
- ²³K. McGlinchey, B. D. Appelbe, A. J. Crilly, J. K. Tong, C. A. Walsh, and J. P. Chittenden, "Diagnostic signatures of performance degrading perturbations in inertial confinement fusion implosions," *Phys. Plasmas* **25**(12), 122705 (2018).
- ²⁴A. J. Crilly, B. D. Appelbe, O. M. Mannion, C. J. Forrest, J. P. Knauer, D. J. Schlossberg, E. P. Hartouni, A. S. Moore, and J. P. Chittenden, "Neutron backscatter edges as a diagnostic of burn propagation," *Phys. Plasmas* **29**(6), 062707 (2022).
- ²⁵A. J. Crilly, N. P. L. Niasse, A. R. Fraser, D. A. Chapman, K. W. McLean, S. J. Rose, and J. P. Chittenden, "SpK: A fast atomic and microphysics code for the high-energy-density regime," *High Energy Density Phys.* **48**, 101053 (2023).
- ²⁶S. T. O'Neill, B. D. Appelbe, A. J. Crilly, C. A. Walsh, D. J. Strozzi, J. D. Moody, and J. P. Chittenden, "Burn propagation in magnetized high-yield inertial fusion," *Phys. Plasmas* **32**(2), 022703 (2025).
- ²⁷A. J. Crilly, D. J. Schlossberg, B. D. Appelbe, A. S. Moore, J. Jeet, S. Kerr, M. Rubery, B. Lahmann, S. O'Neill, C. J. Forrest, O. M. Mannion, and J. P. Chittenden, "Measurements of dense fuel hydrodynamics in the NIF burning plasma experiments using backscattered neutron spectroscopy," *Phys. Plasmas* **31**(4), 042701 (2024).
- ²⁸M. M. Marinak, G. B. Zimmerman, T. Chapman, G. D. Kerbel, M. V. Patel, J. M. Koning, S. M. Sepke, B. Chang, C. R. Schroeder, J. A. Harte, D. S. Bailey, L. A. Taylor, S. H. Langer, M. A. Belyaev, D. S. Clark, J. Gaffney, B. A. Hammel, D. E. Hinkel, A. L. Kritcher, J. L. Milovich, H. F. Robey, and C. R. Weber, "How numerical simulations helped to achieve breakeven on the NIF," *Phys. Plasmas* **31**(7), 070501 (2024).
- ²⁹A. J. Crilly, P. W. Moloney, D. Shi, and E. A. Ferdinandi, "Automated simulation-based design via multi-fidelity active learning and optimisation for laser direct drive implosions," *arXiv:2508.20878* (2025).
- ³⁰D. D. Clayton, *Principles of Stellar Evolution and Nucleosynthesis* (University of Chicago Press, 1983).
- ³¹G. B. Zimmerman, *Recent Developments in Monte Carlo Techniques* (Lawrence Livermore National Laboratory, Livermore, CA, 1990), Vol. 11.
- ³²S. Atzeni and J. Meyer-ter Vehn, *The Physics of Inertial Fusion: Beam-Plasma Interaction, Hydrodynamics, Hot Dense Matter* (Oxford University Press, Oxford, 2004).
- ³³G. S. Fraley, E. J. Linnebur, R. J. Mason, and R. L. Morse, "Thermonuclear burn characteristics of compressed deuterium-tritium microspheres," *Phys. Fluids* **17**(2), 474–489 (1974).
- ³⁴Extending a steady-state ablation analysis¹² to include alpha momentum deposition shows that the induced positive radial pressure gradient also drives faster mass ablation. However, the magnitude of effect is of order $(\rho_{HS}/\rho_{shell})\beta$ and given that the hotspot-shell density contrast is typically large, this effect is second order to shell deceleration.
- ³⁵A. R. Christopherson, R. Betti, J. Howard, K. M. Woo, A. Bose, E. M. Campbell, and V. Gopalaswamy, "Theory of alpha heating in inertial fusion: Alpha-heating metrics and the onset of the burning-plasma regime," *Phys. Plasmas* **25**(7), 072704 (2018).
- ³⁶D. L. Galbraith and T. Kammash, "Fusion product momentum transfer to inertially confined plasma," *Fusion Technol.* **19**(3P1), 492–497 (1991).
- ³⁷Y. Kuroki, Y. Nakao, T. Johzaki, T. Miyahara, H. Nakashima, and K. Kudo, "Fusion product momentum deposition in laser imploded targets," *Nucl. Fusion* **40**(3), 357 (2000).
- ³⁸T. Johzaki, Y. Kuroki, and Y. Nakao, "Two-dimensional analysis of energy and momentum deposition effects of alpha particles in ICF plasmas," in *IAEA Conference Proceedings Fusion Energy 2000* (IAEA, 2001), no. 8/C, 5 p, see <https://inis.iaea.org/records/s7gm0-6fv92>.
- ³⁹J. A. Gaffney, S. T. Brandon, K. D. Humbird, M. K. G. Kruse, R. C. Nora, J. L. Peterson, and B. K. Spears, "Making inertial confinement fusion models more predictive," *Phys. Plasmas* **26**(8), 082704 (2019).
- ⁴⁰R. C. Nora, N. Birge, D. Casey, C. Danly, E. L. Dewald, B. Z. Djordjevic, A. Do, M. Durocher, J. E. Field, D. Fittinghoff *et al.*, "Correlations between asymmetric compression, burn amplification, and hot-spot velocities in inertial confinement fusion implosions," *Phys. Plasmas* **30**(9), 092705 (2023).
- ⁴¹S. Atzeni and A. Caruso, "A diffusive model for α -particle energy transport in a laser plasma," *Il Nuovo Cimento B* **64**(2), 383–395 (1981).
- ⁴²E. G. Corman, W. E. Loewe, G. E. Cooper, and A. M. Winslow, "Multi-group diffusion of energetic charged particles," *Nucl. Fusion* **15**(3), 377 (1975).
- ⁴³R. Ramis and J. Meyer-ter Vehn, "MULTI-IFE—A one-dimensional computer code for Inertial Fusion Energy (IFE) target simulations," *Comput. Phys. Commun.* **203**, 226–237 (2016).
- ⁴⁴G. Zimmerman, D. Kershaw, D. Bailey, and J. Harte, "LASNEX code for inertial confinement fusion," Technical Report No. UCRL-80169 (California University, Livermore; Lawrence Livermore National Laboratory, 1977).
- ⁴⁵H. Bellenbaum, M. Read, N. Niasse, S. Barrett, N. Hawker, N. Joiner, D. Chapman *et al.*, "FLAIM: A reduced volume ignition model for the compression and thermonuclear burn of spherical fuel capsules," *High Energy Density Phys.* **53**, 101159 (2024).

- ⁴⁶K. M. Woo, R. Betti, D. Shvarts, O. M. Mannion, D. Patel, V. N. Goncharov, K. S. Anderson, P. B. Radha, J. P. Knauer, A. Bose, V. Gopalaswamy, A. R. Christopherson, E. M. Campbell, J. Sanz, and H. Aluie, "Impact of three-dimensional hot-spot flow asymmetry on ion-temperature measurements in inertial confinement fusion experiments," *Phys. Plasmas* **25**(10), 102710 (2018).
- ⁴⁷B. Appelbe, M. Sherlock, O. El-Amiri, C. Walsh, and J. Chittenden, "Modification of classical electron transport due to collisions between electrons and fast ions," *Phys. Plasmas* **26**(10), 102704 (2019).
- ⁴⁸B. Appelbe, A. L. Velikovich, M. Sherlock, C. Walsh, A. Crilly, S. O' Neill, and J. Chittenden, "Magnetic field transport in propagating thermonuclear burn," *Phys. Plasmas* **28**(3), 032705 (2021).
- ⁴⁹M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, and R. J. Mason, "Ignition and high gain with ultrapowerful lasers," *Phys. Plasmas* **1**(5), 1626–1634 (1994).
- ⁵⁰S. Palaniyappan, E. N. Loomis, S. D. Negussie, J. P. Sauppe, R. L. Scott, H. F. Robey, N. S. Christiansen, P. M. Donovan, C. S. Wong, L. Kot *et al.*, "First indirectly driven liquid-DT filled double shell implosions at the National Ignition Facility," *Phys. Plasmas* **32**(10), 102706 (2025).
- ⁵¹M. E. Cuneo, M. C. Herrmann, D. B. Sinars, S. A. Slutz, W. A. Stygar, R. A. Vesey, A. B. Sefkow, G. A. Rochau, G. A. Chandler, J. E. Bailey *et al.*, "Magnetically driven implosions for inertial confinement fusion at Sandia National Laboratories," *IEEE Trans. Plasma Sci.* **40**(12), 3222–3245 (2012).