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Burn Propagation in Inertial Confinement Fusion

Introduction

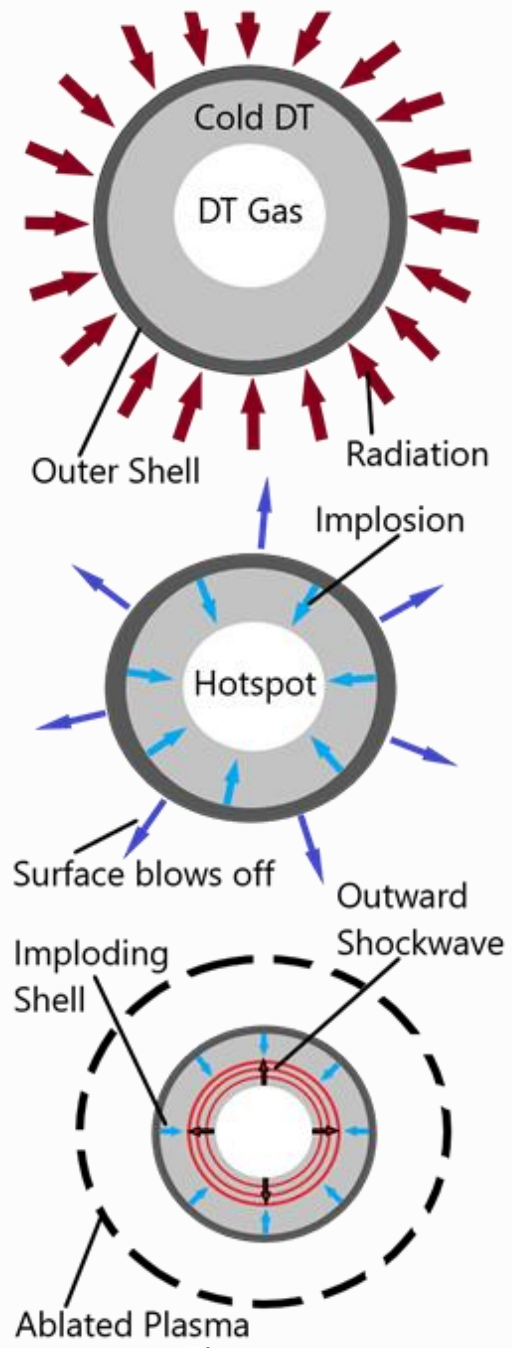

Figure 1

The National Ignition Facility

.The National Ignition Facility (NIF), the largest inertial confinement fusion (ICF) laboratory, achieved 1.3 MJ [1] —the highest ICF yield yet—in an experiment in August 2021 (NIF210808).

.At the NIF, a deuterium-tritium (DT) ice shell filled with DT gas is irradiated, causing inward shocks.

.The shocks superimpose at the center, heating the fuel by mechanical work . When the central pressure dominates, a 'hotspot' surrounded by colder and dense DT fuel forms — see Figure 1.

.Once the hotspot is hot enough, DT fusion (D + T → α + neutron) occurs. The alpha particles produced increase the DT temperature via Coulomb collisions, triggering more fusion.This positive feedback initiates a propagating burn wave of fusion reactions outwards, hence amplifying yield significantly [2].

Types of propagating burn waves

.Deflagration waves: rarefactions which travels at subsonic speeds and form after a significant deposition of alpha particles and electron thermal conduction in the dense fuel layer.

.Detonation waves: shock waves which travel at supersonic speeds and form when alpha heating is large enough to create a pressure imbalance [3].

.Key indicators of detonation are when (1)the detonation front travels faster than the sound speed in the material and (2) the mechanical work heatingdominates ahead of-heating and electron thermal conduction.

Project Aim

.Currently only deflagration waves have been observed. Achieving detonation would be ground-breaking in establishing the viability of fusion as a future clean energy source since detonation would achieve yields substantially higher than deflagration.

.In this project, the deflagration to detonation transition is studied and the probability of achieving detonation on the NIF is explored.

Simulations & Analysis

In this project, 1D simulations based on NIF210808 parameters were executed using the radiation-magnetohydrodynamics code Chimera developed by Imperial. Chimera solves multiple energy equations that occur during ICF and outputs variables for each timestep. Python was then used to analyse this data.

Deflagration

.The NIF210808 simulation with the target dimension and implosion time-scale scaled by a factor of 1.1 is used to demonstrate deflagration.

.Figure 2 shows the time-evolution of the density, temperature and pressure. The temperature continues to rise even after hotspot formation.

.The hotspot power density contributions (alpha heating W_{α}, mechanical work W_{PdV}, radiation W_{γ} and electron thermal conduction W_e) are shown in Figure 3. The alpha particles deposit majority of their energy at the dense fuel layer and therefore form a sharp Bragg peak.

.This deflagration simulation results in a large yield of ~ 8MJ .

.However W_e dominates and W_{α} levels are not sufficiently high to form a pressure imbalance.

Detonation

.NIF210808 parameters were varied. However, for a NIF-like capsule the areal density of the cold fuel, ρR_{cf} , is not high enough to confine the hotspot for long enough to allow a detonation wave to develop.

.Instead an idealised problem, which does not utilise an external radiation source and assumes that alpha particles deposit their energy where they form, is used to demonstrate detonation—see Figure 4.

.The deflagration to detonation transition can be seen in Figure 5 when the W_{PdV} peak overtakes the W_{α} and W_e peaks. The large ρR_{cf} allows a pressure imbalance to form which is ~100 times greater than the pressure in the deflagration simulation.

.Deflagration waves can also travel supersonically, thus making it to hard distinguish between deflagration and detonation using the sound speed method.

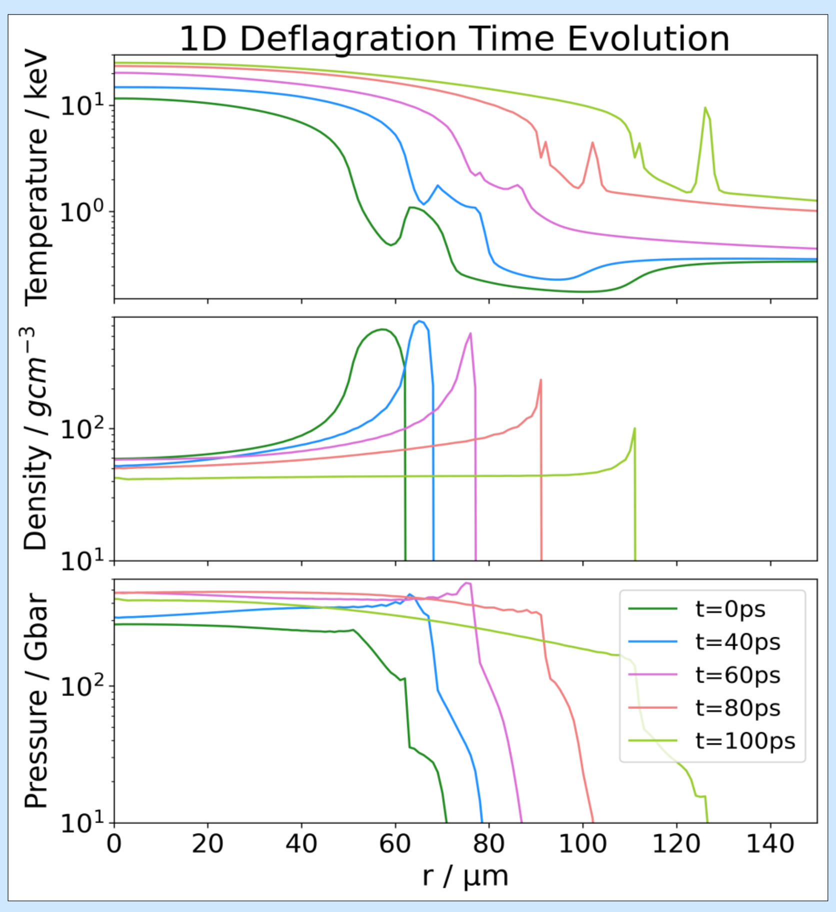

Figure 2

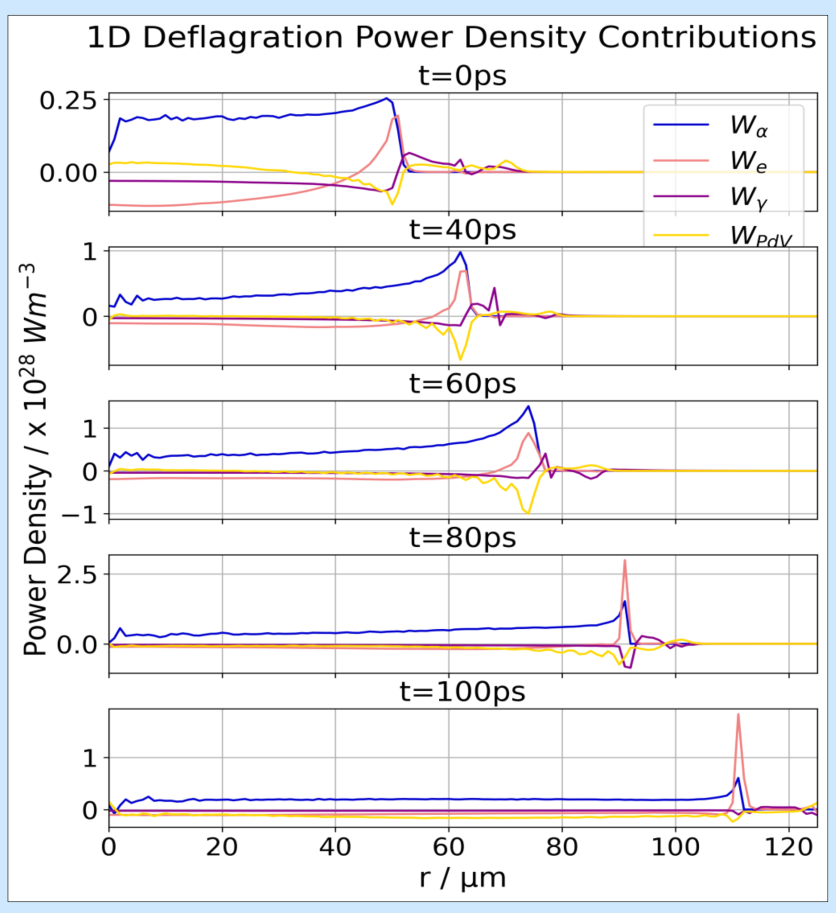

Figure 3

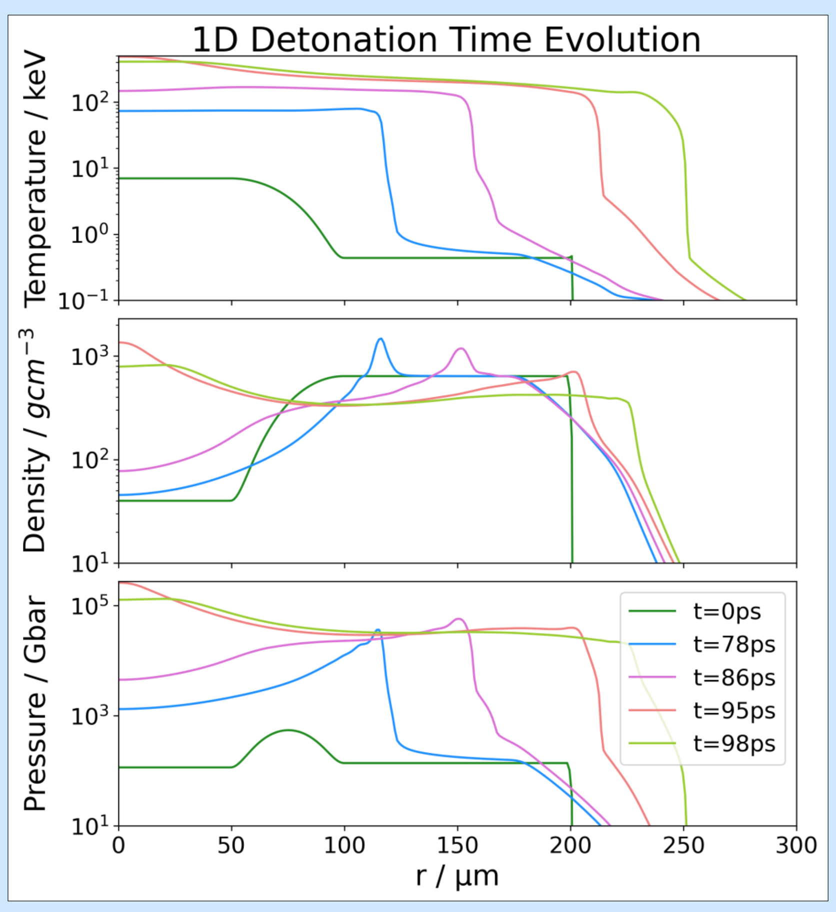

Figure 4

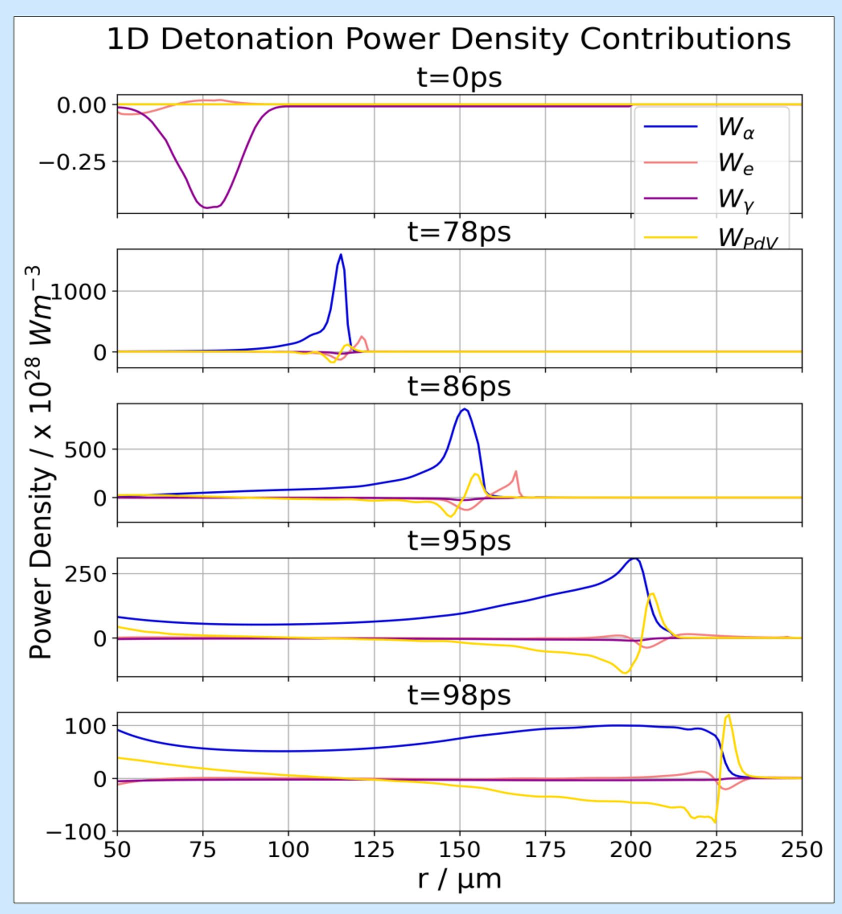

Figure 5

Conclusion

.Changing the input parameters for a NIF-like capsule did not result in detonation. The idealized problem was the most promising test-run to demonstrate detonation, as W_{PdV} dominates at the shock front (Figure 5). However, volumetrically most of the power in the capsule is provided by alpha heating. Whether this is classed as a detonation is dependent on which argument is considered more valid.

.Alpha and mechanical work heating are intrinsically linked and cannot be detangled. Therefore, a robust definition of detonation needs to be established before a deflagration to detonation transition can be identified definitively.

.This study has shown that areal density is the key parameter which affects the likelihood of detonation. Since high areal densities cannot be achieved with current technology, this is a factor that future experiments should consider when studying detonation.

References

[1] Dunning and S. Campus, "Major nuclear fusion milestone reached as 'ignition' triggered in a lab | Imperial News | Imperial College London", Imperial News, 2021.
[2] S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion. Oxford Scholarship Online, 2004.
[3] A. Christopherson, R. Betti, S. Miller, V. Gopalaswamy, O. Mannion and D. Cao, "Theory of ignition and burn propagation in inertial fusion implosions", Physics of Plasmas, vol. 27, no. 5, p. 052708, 2020