Theory of Ignition and Burn Propagation in Inertial Fusion Implosions

A. R. Christopherson,[1,2] R. Betti,[1,2,3] S. Miller,[1,2] V. Gopalaswamy,[1,2] O. M. Mannion,[1,3] and D. Cao[1]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Department of Mechanical Engineering, University of Rochester
[3]Department of Physics & Astronomy, University of Rochester

A large effort is currently underway to demonstrate thermonuclear ignition in the laboratory via inertial confinement fusion (ICF).[1] ICF uses laser-driven implosions of a solid deuterium–tritium (DT) shell to achieve ignition conditions.[2,3] Ignition is a thermal instability of a DT plasma driven by the energy deposition of the alpha particles ("alpha heating") produced by the fusion reaction D + T = α(3.5 MeV) + n(14.1 MeV). Ignition has never been achieved in a laboratory plasma, and its demonstration is widely viewed as a major scientific achievement with important applications to fusion energy generation and to the stewardship of the nuclear stockpile. Unlike in steady-state plasmas, as those envisioned for magnetic confinement fusion,[4] assessing ignition in ICF is greatly complicated by the transient nature of implosions and the fact that ignition starts from the central hot region ("hot-spot ignition") and then propagates to the cold and dense surrounding fuel ("burn-wave propagation"). The fundamental mechanism at the basis of ignition is alpha heating of the DT fuel and its positive feedback on the fusion reaction rate.

Current experiments at the National Ignition Facility have demonstrated significant alpha heating, leading to amplifications of the fusion yield close to threefold.[5–7] Despite much work on assessing and measuring the degree of alpha heating, two crucial questions remain unanswered with regard to ignition: (1) What is ignition in inertial fusion; and (2) what fusion yields are required in ICF to claim that ignition has taken place. In the past, common metrics for ignition have related the fusion yield to the incident laser energy on target. The so-called *target gain* = 1 condition has been widely used as the ultimate indicator of ignition.[8] Here, target gain is the ratio of the fusion energy output to the laser energy on target. Such a metric is not rooted in the burning-plasma physics of DT fuel and is unrelated to the onset of ignition. It is motivated only by its implications to fusion energy, where an energy output greater than the input is required for any viable fusion scheme. This metric is not an indicator of the onset of the thermonuclear instability and therefore cannot be used to measure the ignition point.

In this work, we provide a physical definition of hot-spot ignition in ICF, which is of general validity for laser fusion. This definition of ignition identifies the onset of the thermal runaway within the hot spot of an ICF implosion just prior to the burn propagation in the dense fuel. To identify the ignition point, we first search for qualitative features distinguishing runaway burn in the entire fuel volume from sub-ignition alpha heating. The first distinctive feature is related to the different behavior of the yield amplification for implosions in the alpha-heating regime versus implosions with propagating burn. Here the yield amplification = $Y_\alpha / Y_{\text{no}\,\alpha}$, where Y_α is the fusion yield measured in an experiment and $Y_{\text{no}\,\alpha}$ is the estimated yield without accounting for alpha-particle energy deposition. It was shown in Ref. 9 that in the alpha-heating regime, the yield amplification depends uniquely on the dimensionless parameter f_α given by

$$f_\alpha \equiv \frac{1}{2}\frac{\theta_\alpha E_\alpha}{E_{\text{hs}}}, \tag{1}$$

where E_α is the total alpha-particle energy, θ_α is the fraction of alpha particles deposited into the hot spot, and E_{hs} is the hot-spot internal energy at bang time (when the neutron-production rate is maximized). The parameter f_α is designed to compare the deposited alpha energy to the hot-spot internal energy at bang time. In the numerator, $E_\alpha = \varepsilon_\alpha \cdot$ Yield, where $\varepsilon_\alpha = 3.5$ MeV and Yield is the neutron yield. The factor 1/2 accounts for the fact that approximately one half of all of the fusion alphas produced have deposited their energy into the hot spot at bang time. In defining E_{hs}, the hot-spot radius is the point where the neutron-production rate drops to 17% of its maximum value. The Lagrangian trajectory of this hot spot is then back calculated in time to determine the fraction of alpha particles absorbed in the hot spot, as was done in Refs. 10 and 11.

In Fig. 1, the yield amplification resulting from alpha heating is plotted as a function of f_α, where the yield amplification curves for many different targets are shown to overlap up to a critical value of $f_\alpha = 1.4$. The simulation ensemble shown here contains implosion velocities between 200 km/s and 600 km/s, laser energies between 30 kJ and 10 MJ, and adiabats between 1 and 6, where the adiabat[12] is given for DT by $\alpha = P/2.2\rho^{5/3}$, with the shell pressure P in megabars and the plasma density in g/cm^3. The database was generated by creating many ignited implosions with a variety of different target gains and then degrading them by reducing the implosion velocity, increasing the adiabat, or by applying density modulations to the inner shell surface. Ignition occurs at the critical value $f_\alpha = 1.4$ corresponding to a yield amplification due to alpha heating of about 15× to 25×. For $f_\alpha < 1.4$, alpha heating is mostly confined to the hot spot, while for $f_\alpha > 1.4$, the ablation of shell mass into the neutron-producing region significantly increases the fusion output.

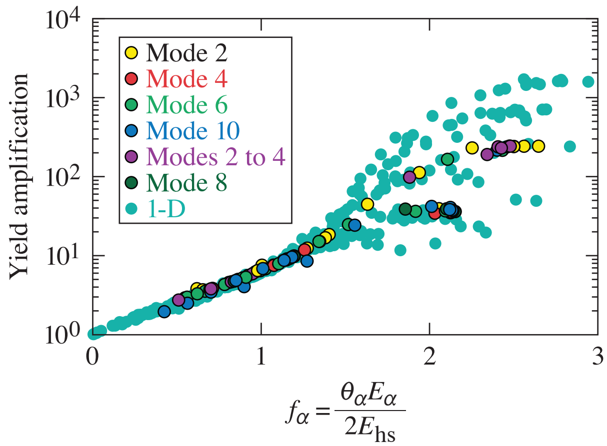

Figure 1
The yield amplification is plotted as a function of f_α for the ensemble of 1-D *LILAC*[13] and 2-D *DRACO*[14] simulations. In the alpha-heating regime ($f_\alpha < 1.4$), the yield amplification depends uniquely on f_α regardless of the target mass, areal density, and temperature. After $f_\alpha = 1.4$, shell mass and burnup fraction determine the maximum fusion yield.

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