

# Thermonuclear ignition and the onset of propagating burn in inertial fusion implosions

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A large effort is currently under way to demonstrate thermonuclear ignition in the laboratory via inertial confinement fusion (ICF) [1]. In laser driven inertial confinement fusion (ICF), a spherical capsule of deuterium and tritium (DT) is driven to high velocities by direct irradiation of laser energy (direct drive) or an x-ray bath of an irradiated hohlraum (indirect drive) [2]. At stagnation, the final fuel assembly consists of a low-density (30-100 g/cc), high-temperature (5 -10 keV) core -the hot spot- surrounded by a dense (300 -1000 g/cc), cold (200 - 500 eV) fuel layer - the compressed shell. Such plasma conditions are sufficient for initiating DT thermonuclear fusion when a deuteron and triton fuse to produce a 14.1 MeV neutron and a 3.56 MeV alpha particle. The alpha particle primarily deposits energy in the plasma by colliding with electrons, raising the hot spot temperature and further increasing the fusion reaction rate. This positive feedback cycle is called "alpha heating" and ignition is a direct consequence of the resulting thermal instability. Ignition has yet to be 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 [3]. 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").

Recent experiments at the National Ignition Facility (NIF) have demonstrated significant alpha heating leading to significant amplifications of the fusion yield close to 3 folds [5]. Despite much work on assessing and measuring the degree of alpha heating, there are two crucial questions still 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 this work, we try to answer both questions. We first provide a physical definition of hot spot ignition in ICF and then provide an approximate formula for the fusion energy yield corresponding to the ignition point. The definition of ignition is of general validity for laser fusion and it 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. It is shown in this Letter that the onset of burn propagation can be uniquely identified through the dimensionless parameter  $f_\alpha$  which compares the deposited alpha particle energy to the hot spot's internal energy:

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

where  $E_\alpha$  is the total alpha-particle energy,  $\theta_\alpha$  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). In Figure 1, the yield amplification is plotted as a function of  $f_\alpha$  for a simulation ensemble of 1-D LILAC[6] simulations with different masses, convergence ratios, and hot spot temperatures (turquoise points). The rest of the colored points respectively represent 2-D DRACO[7] simulations of implosions where a density modulation has been applied to the shell's inner surface. Ignition occurs at the critical value  $f_\alpha \approx 1.4$  corresponding to a yield amplification due to alpha heating of about 15x to 25x [8,9]. For  $f_\alpha < 1.4$ , alpha-heating is mostly confined to the hot spot and the yield amplification depends uniquely on the level of alpha-heating within the hot spot (represented by  $f_\alpha$ ). For  $f_\alpha > 1.4$ , the burn front propagates into the dense shell which significantly amplifies the fusion producing mass and yield. In this regime, the shell's areal density plays a dominant role in determining the fusion yield enhancement.

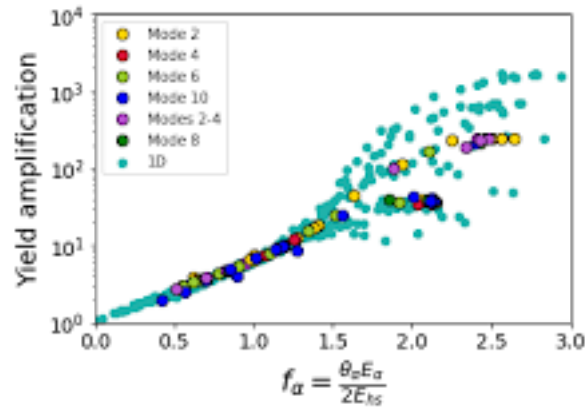


Figure 1:

The next step is to relate the fusion yield required for marginal ignition (at a yield amplification of 20) to the fuel mass and areal density. In Ref.[10], it was shown that a large enhancement in the fusion yield was correlated to the parameter

$$\chi_{no\alpha} \equiv \left( \rho R \right)^{0.61} \left( \frac{0.12 \text{ Yield}_{16}}{M_{stag}} \right)^{0.34},$$

where  $M_{stag}$  is the stagnated DT mass in mg,  $\rho R$  is the neutron averaged fuel areal density in  $g/cm^2$ , and  $\text{Yield}_{16}$  is the neutron yield in units of  $10^{16}$  neutrons. The parameter  $\chi_{no\alpha}$  is computed from simulations without alpha transport and  $\chi_{no\alpha} \simeq 1$  represents the plasma conditions due to pure hydrodynamic compression which are required for ignition. It follows that we can expect marginal ignition to occur in the neighborhood of  $\chi_{no\alpha} \simeq 1$  which allows us to relate the fusion yields of marginally ignited implosions to their designed areal densities and mass. For marginally ignited targets, we obtain the following least squares fit:

$$Y_{ign} \text{ (MJ)} \approx \left( \frac{M_{stag} \text{ (mg)}}{0.21} \right)^{0.81} \left( \frac{1}{\rho R \text{ (g/cm}^2\text{)}} \right)^{2.61}.$$

This equations provides a formula relating the fusion yield required to claim ignition to the designed fuel areal density and stagnated mass. It is important to note that the lower the areal density implosions require higher fusion yields for ignition.

In summary, the ignition condition for inertially confined plasmas has been identified as the transition from thermal instability of the hot spot to propagating burn in the shell. Using a large ensemble of 1D and 2D simulations, we show that this definition of ignition is valid in the presence of asymmetries and differences in shell adiabat and kinetic energy. Ignition corresponds to a yield amplification of 15x to 25x and a value of  $f_\alpha \simeq 1.4$ .

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## Affiliation

Laboratory for Laser Energetics

## Country or International Organization

United States

**Primary authors:** Ms CHRISTOPHERSON, Alison; CAO, Duc (Laboratory for Laser Energetics); VARCHAS, Gopalaswamy (Laboratory for Laser Energetics); MANNION, Owen (Laboratory for Laser Energetics); BETTI, Riccardo (Laboratory for Laser Energetics); MILLER, San (Laboratory for Laser Energetics)

**Presenter:** Ms CHRISTOPHERSON, Alison

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