Impact of Areal-Density Asymmetries on the Loss of Confinement and Ignition Threshold in Inertial Confinement Fusion Capsules

K. M. Woo and R. Betti

Laboratory for Laser Energetics, University of Rochester

In inertial confinement fusion implosion experiments, variations in the shell areal density ρR reduce the shell's inertia to confine the core pressure. Distorted capsules with large areal-density modulations decompress faster than uniform capsules in the disassembly phase. In this summary, a simple 3-D analytic hot-spot model is derived to include the effects of low-mode areal-density modulations in the ignition criterion. The generalized 3-D ignition criterion for low modes is shown to depend on both the harmonic mean and the arithmetic mean of the areal density. The "thin spots" in the shell are shown to dominate the loss of confinement as reflected by the harmonic mean definition of areal densities.

Effects of low-mode asymmetries on confinement can be described by a highly idealized ignition model. In this analysis, the 3-D hot-spot energetics in the disassembly phase are studied by a simple form of the 3-D hot-spot energy equation [Eq. (9) in Ref. 1]

$$\frac{\mathrm{d}}{\mathrm{d}t}\ln\left(PV^{\gamma}\right) = P\big/S_{\mathrm{f}}. \tag{1}$$

Here $S_{\mathrm{f}} \equiv 24\,T_{\mathrm{i}}^2\big/\left(\langle\sigma v\rangle_{\mathrm{DT}}E_{\alpha}\right)$ is approximated with a constant, valid for DT fusion reactivities $\langle\sigma v\rangle_{\mathrm{DT}}$ within the ion-temperature range $6 < T_{\mathrm{i}} < 20$ keV; $S_{\mathrm{f}} \simeq 7.24$ atm s is the minimum ignition threshold;[2,3] $\gamma = 5/3$ is the ratio of specific heat for an ideal gas; and $E_{\alpha} = 3.5$ MeV is the DT fusion alpha particle's initial kinetic energy; heat conduction loss and radiation loss are neglected. The time evolution of the hot-spot volume V is approximated by a second-order expansion of V in time t after the capsule is compressed to the minimum volume. Hereafter, quantities with the subscript "s" are evaluated at the stagnation time t_{s}, which is the moment of the minimum hot-spot volume. For igniting capsules, the hot-spot pressure P grows rapidly as the rate of alpha heating exceeds the rate of PdV work in the disassembly phase. As a result, the generalized 3-D ignition threshold is obtained, $\chi_{3\text{-D}} \equiv P_{\mathrm{s}}\tau_{\mathrm{c}}\big/S_{\mathrm{f}} \rightarrow 1$ as the hot-spot pressure grows to infinity in Eq. (1). The confinement time $\tau_{\mathrm{c}} = \left(V_{\mathrm{s}}\big/\ddot{V}_{\mathrm{s}}\right)^{1/2}$ is given by the second time derivative of the hot-spot volume V_{s}. The impact of areal-density asymmetries on the loss of confinement is hidden in the second time derivative of the hot-spot volume. It can be shown that the confinement time depends on the harmonic mean (HM) definition of areal densities:

$$\tau_{\mathrm{c}} \approx \sqrt{\frac{V_{\mathrm{s}}}{P_{\mathrm{s}}A_{\mathrm{s}}}\langle\rho R\rangle_{\mathrm{HM}}}, \tag{2}$$

where A_{s} is the hot-spot surface area at stagnation. In the harmonic mean definition, the areal densities of thinner regions are weighted more than that of thicker regions. As a result, in the presence of low modes, the hot spot disassembles faster, leading to a shorter confinement time τ_{c} with respect to 1-D since $\langle\rho R\rangle_{\mathrm{HM}} < \rho R_{1\text{-D}}$. The harmonic mean is the only way to account for "thin spots" (areas of ultralow areal density) in the shell that dominate the loss of confinement. If localized, thin spots do not significantly contribute to the arithmetic mean of the areal density. Measuring only the arithmetic mean would overestimate the confinement and therefore the Lawson parameter in the presence of severe asymmetries, leading to areas of ultralow areal density.

As shown in Fig. 1(a), the no-α Lawson criterion $\chi_{\text{no}\,\alpha}^{3\text{-D}} = P_{\mathrm{s}}\tau_{\mathrm{c}}\big/S_{\mathrm{f}}$ is shown to capture the onset of ignition for low modes $\ell =$ 1 to 2 when $\chi_{\text{no}\,\alpha}^{3\text{-D}} \approx 1$. The confinement time τ_{c} is calculated from the curvature of the temporal hot-spot volume at stagnation as the hot spot is compressed to the minimum volume. The yield amplification is shown to be well approximated by the fitting formula $Y_{\text{amp}}^{3\text{-D}} \approx \left(1-\chi_{\text{no}\,\alpha}^{3\text{-D}}/0.96\right)^{-1.14}$. In Fig. 1(b), the harmonic mean ρR of mode $\ell = 1$ is shown to degrade faster with the ion-temperature ratio $T_{\text{min}}/T_{\text{max}}$ than that of the arithmetic-mean ρR. This result implies that the 1-D values of areal densities can be inferred from the measured ion-temperature measurement asymmetry. Consequently, the degradation of the 3-D Lawson criterion $\chi_{\text{no}\,\alpha}^{3\text{-D}}$ for $\ell = 1$ asymmetries can be assessed as a unique function of the ion-temperature measurement asymmetry.

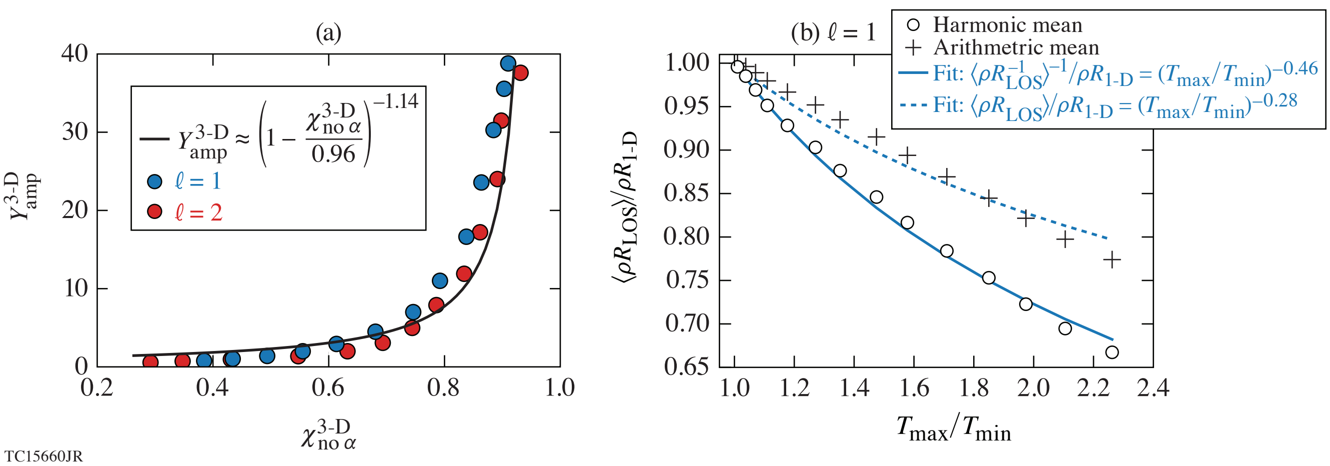

Figure 1
(a) Yield amplification as a function of the no-α Lawson criterion $\chi_{\text{no}\,\alpha}^{3\text{-D}}$ using the confinement time τ_c defined by the second time derivative of the hot-spot volume at the time when the capsule is compressed to the minimum volume. (b) The degradation of harmonic-mean and arithmetic-mean areal densities against the ion-temperature measurement asymmetry.

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