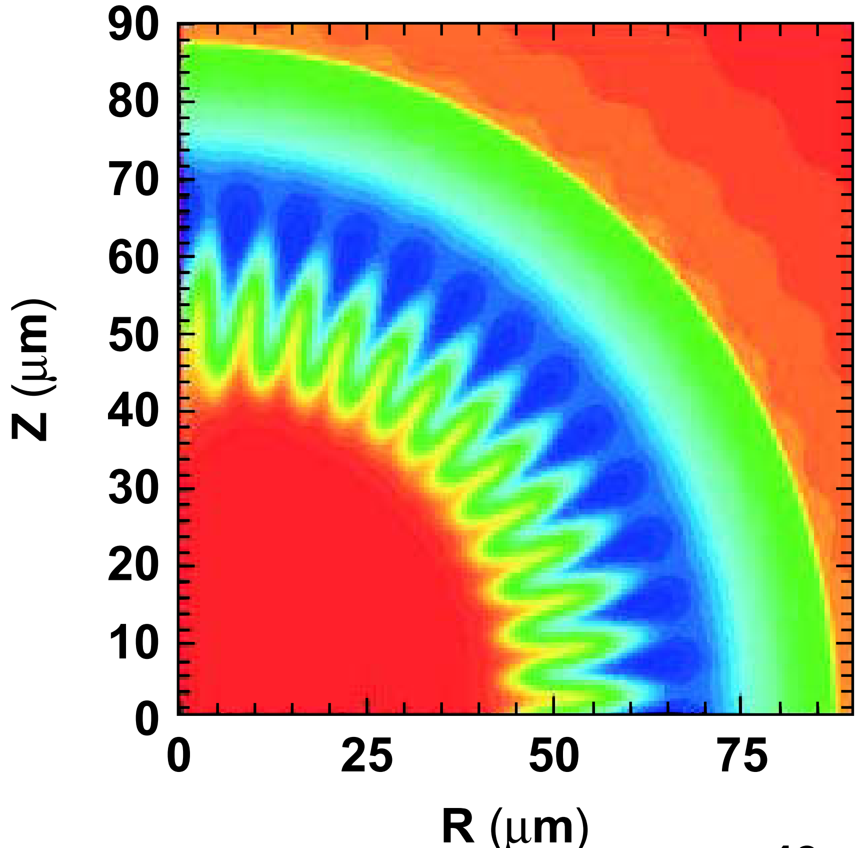
Deceleration Phase of Inertial Confinement Fusion Implosions



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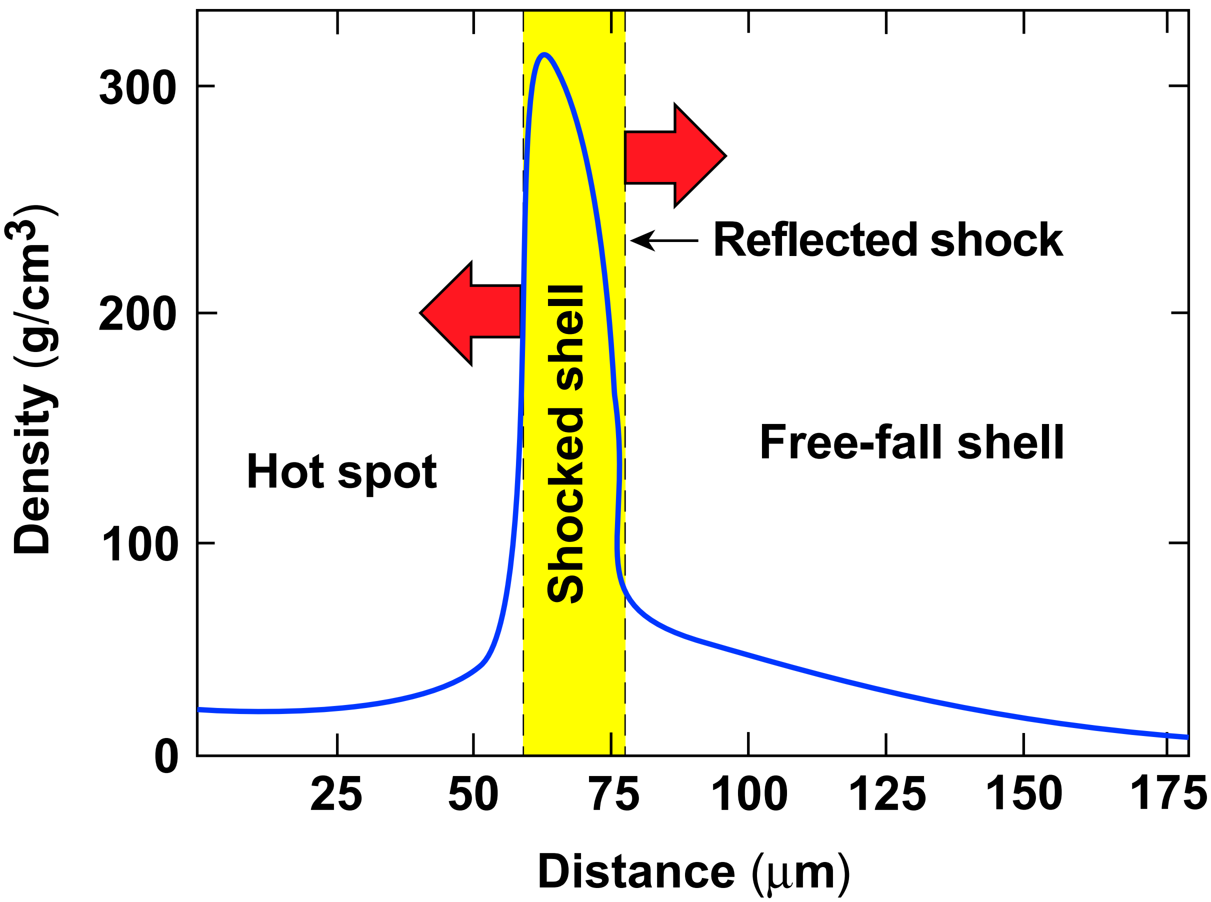
Outline

Mass ablation off the shell into the hot spot changes the classical picture of ICF ignition and deceleration-phase RT instability

- Hot-spot hydrodynamics
- Ablative stabilization of the deceleration-phase Rayleigh–Taylor instability
- Shell hydrodynamics and marginal ignition

Three regions of the capsule can be identified: the hot spot, the shocked shell, and the free-fall shell

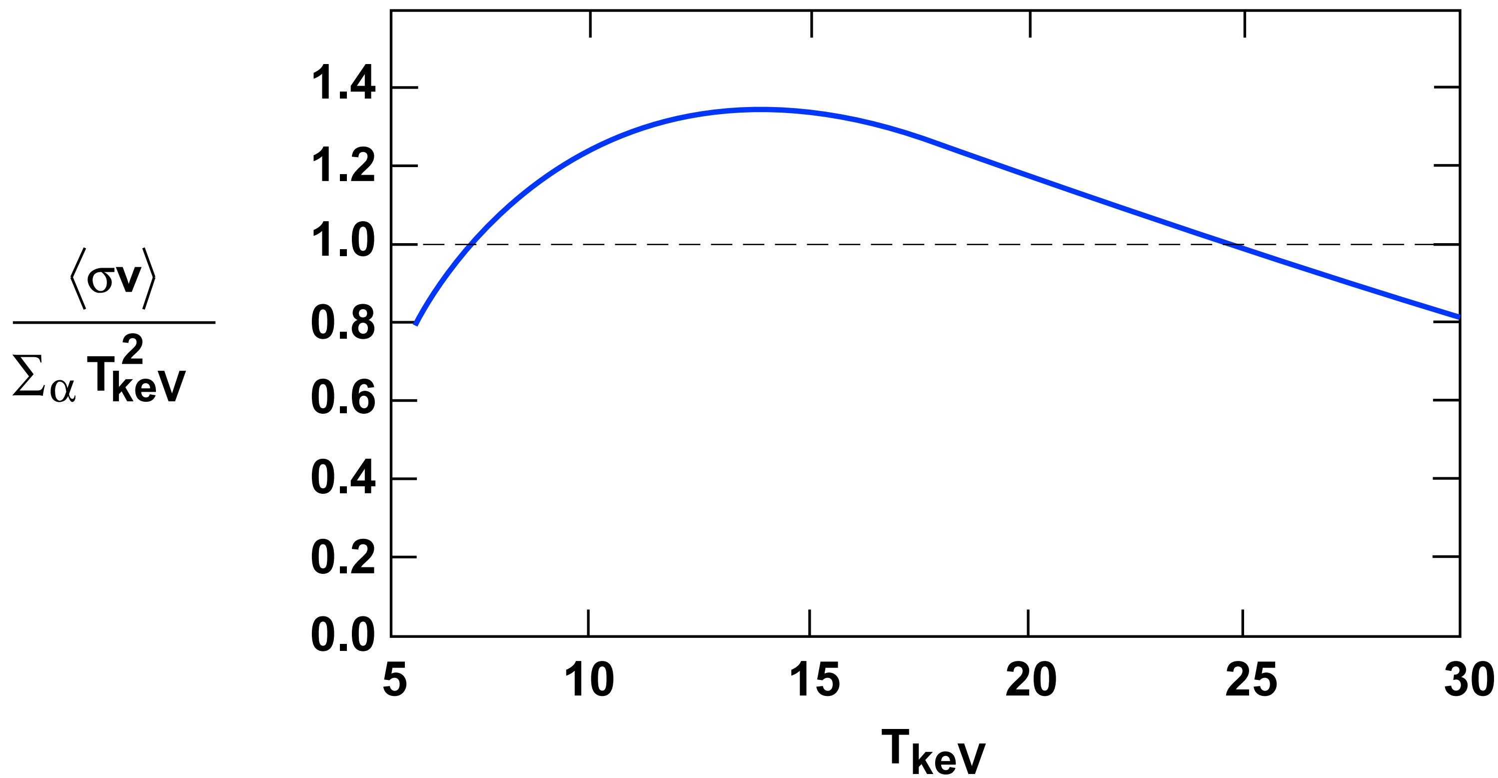


TC5763

The hot spot

The model for the hot spot assumes subsonic flow, $\langle \sigma v \rangle$ proportional to T^2, and local alpha deposition

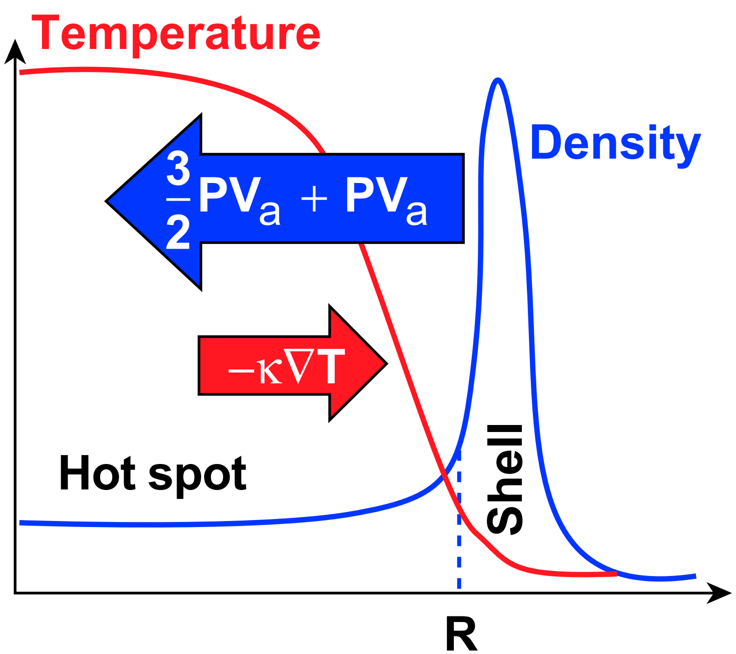
$P \approx P(t)$	$\langle \sigma v \rangle \approx \Sigma_\alpha T^2$	$\kappa = \kappa_0 T^{5/2}$
isobaric	Fusion cross section	Spitzer conduction

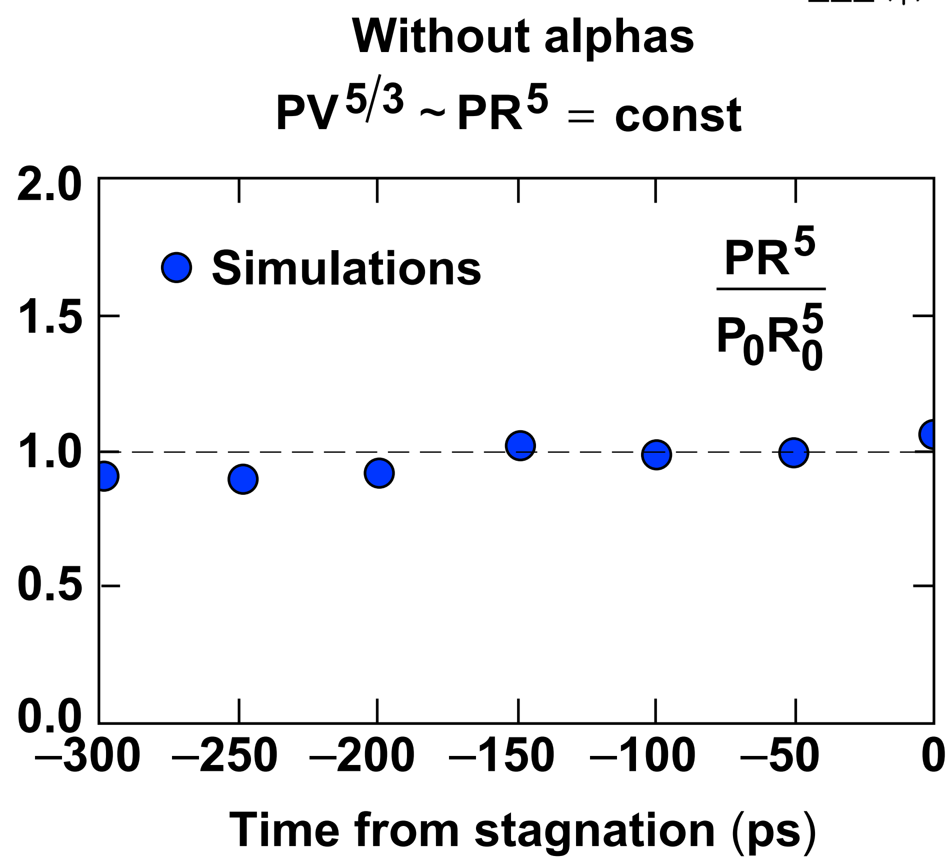


$\Sigma_\alpha = 9.65 \bullet 10^{-19} \text{cm}^3/\text{s keV}^2$

TC5764

The heat flux leaving the hot spot is recycled into the hot spot by mass ablation. In the absence of alpha heating, the hot spot is adiabatic





With alphas

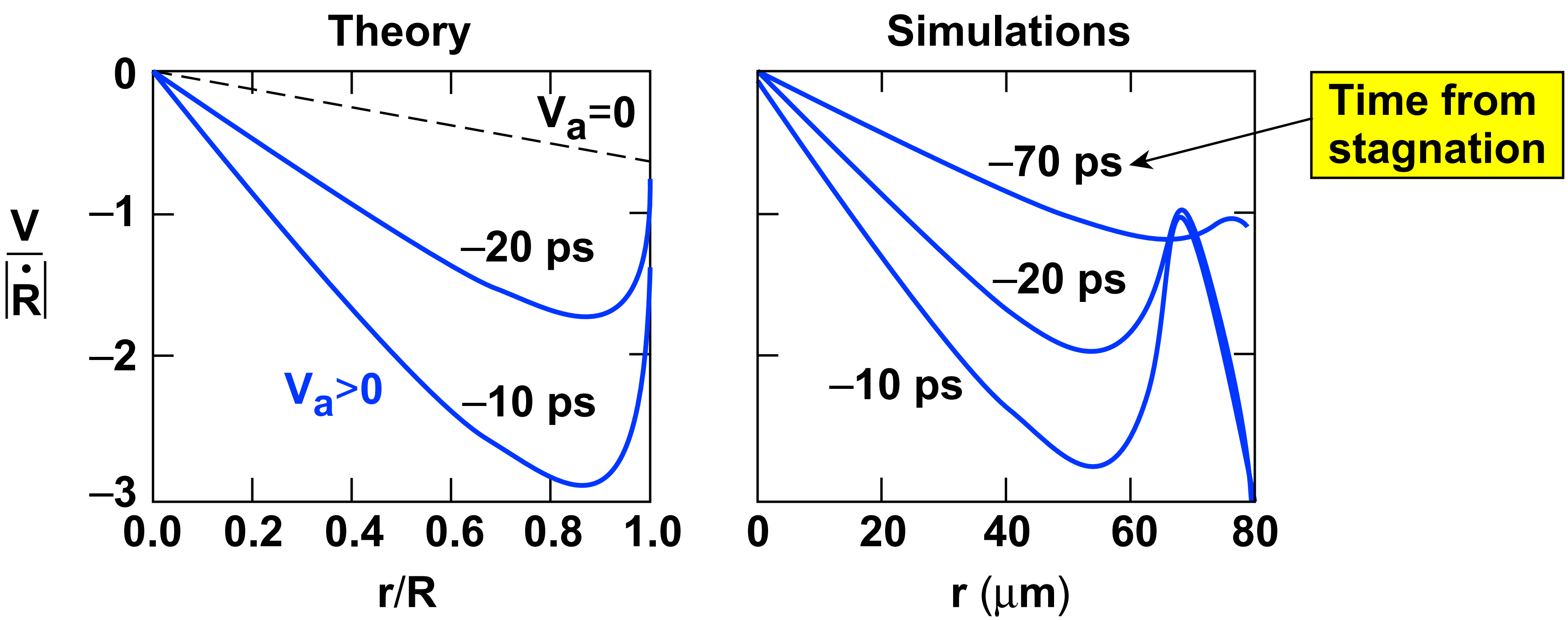
$$\frac{d}{dt}\left(PR^3\right) = \frac{5}{3}D_\alpha P^2R^3 - 2PR^2\dot{R};\; D_\alpha = 0.046\ \text{Gbar}^{-1}\text{ns}^{-1}$$

TC5765

Ablation produces a characteristic “bump” in the hot-spot velocity profile

Hot-spot profiles

$$T \approx T_0(t)\frac{\left(1-\hat{r}^2\right)^{2/5}}{1-0.15\hat{r}^2} \qquad \frac{V}{|\dot{R}|} \approx -\bar{r} - \chi(\hat{r})\frac{\rho_{shell}(t)}{\rho_{hs}(\hat{r},t)}\frac{V_a(t)}{|\dot{R}|} \qquad \hat{r} = \frac{r}{R}$$

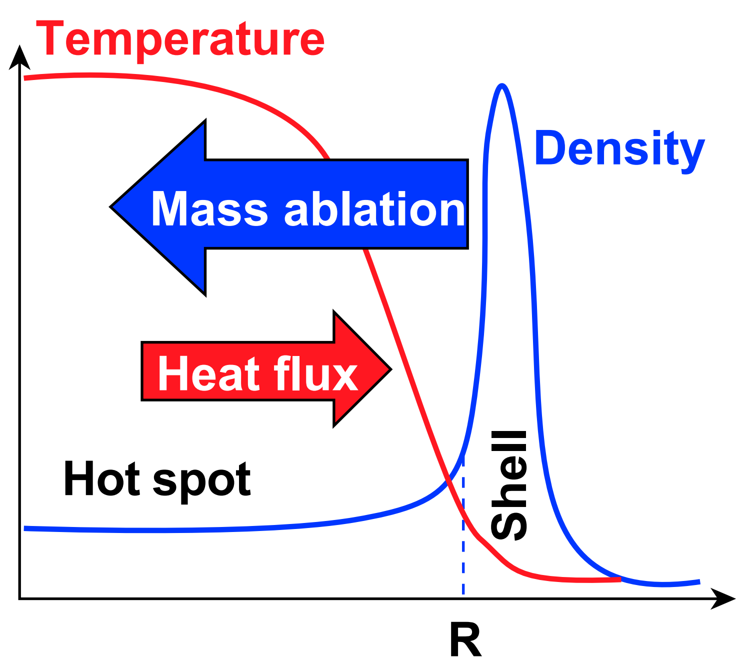


TC5766

R. Betti *et al.*, in press in Physics of Plasmas (Dec. 2001)

The hot-spot mass increases due to mass ablation off the shell

Hot-spot mass: $M = \left\{ M_{gas}^{7/2} + 270\,\kappa_0 m_i \int_0^t P(t')^{5/2} R(t')^{17/2} dt' \right\}^{2/7}$



$\dot{M} = 4\pi R^2 \rho_{shell} V_a$

Rate of change of hot-spot mass

Mass flow through hot-spot surface

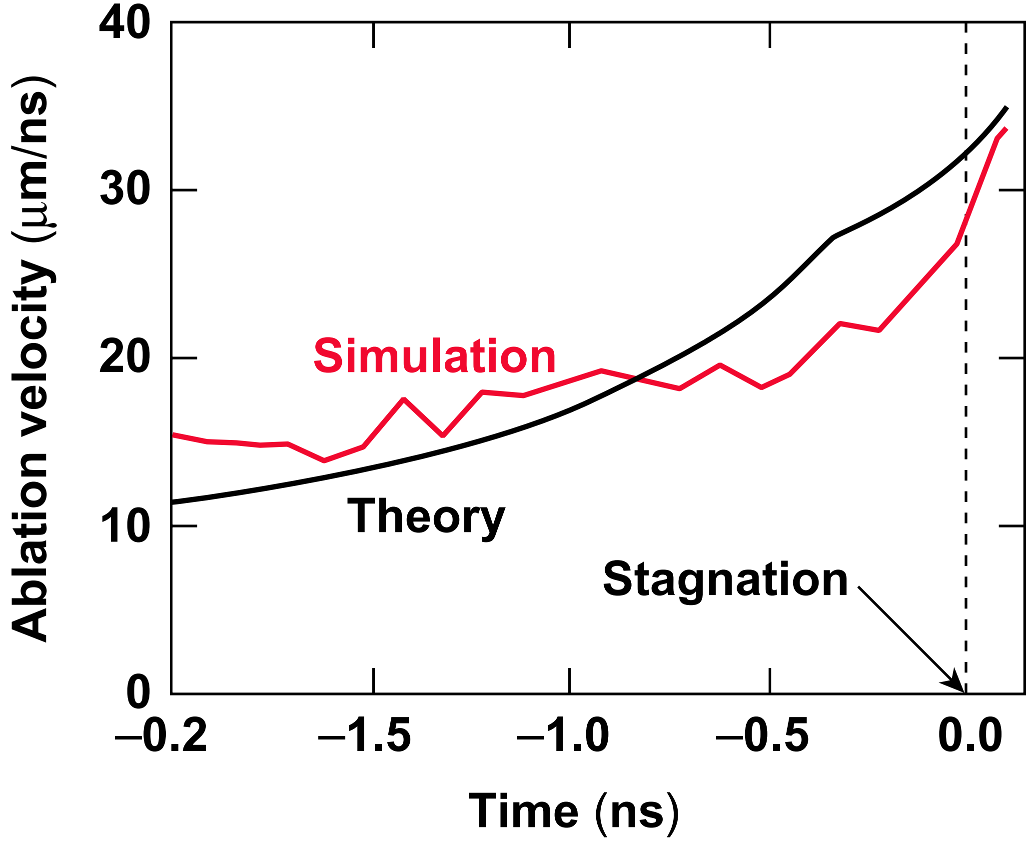
$t = 0 \rightarrow$ beginning of deceleration phase; $\kappa_{Spitz} = \kappa_0 T^{5/2}$

TC5767

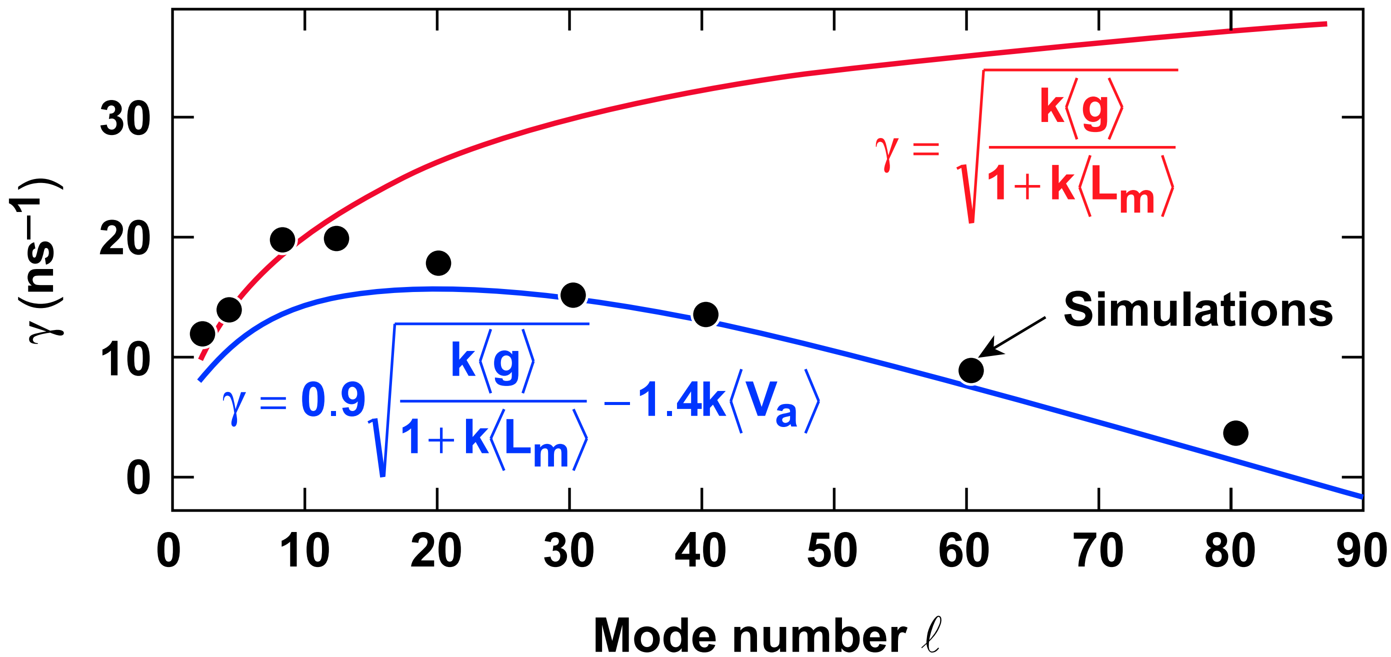
For a direct-drive NIF capsule, the ablation velocity varies between 12 and 30 μm/ns during the 200-ps interval before stagnation

Ablation velocity from theory:

$$V_a = 25\ (\mu m/ns)\left(\frac{T_{keV}}{10}\right)^{5/2}\left(\frac{50}{R_{\mu m}}\right)\frac{300}{\rho^{shell}_{g/cm^3}}$$



Two-dimensional high-resolution simulations confirm the theoretical results for direct drive NIF capsules



$$\gamma = 0.9\sqrt{\frac{k\langle g\rangle}{1+k\langle L_m\rangle}} - 1.4k\langle V_a\rangle$$

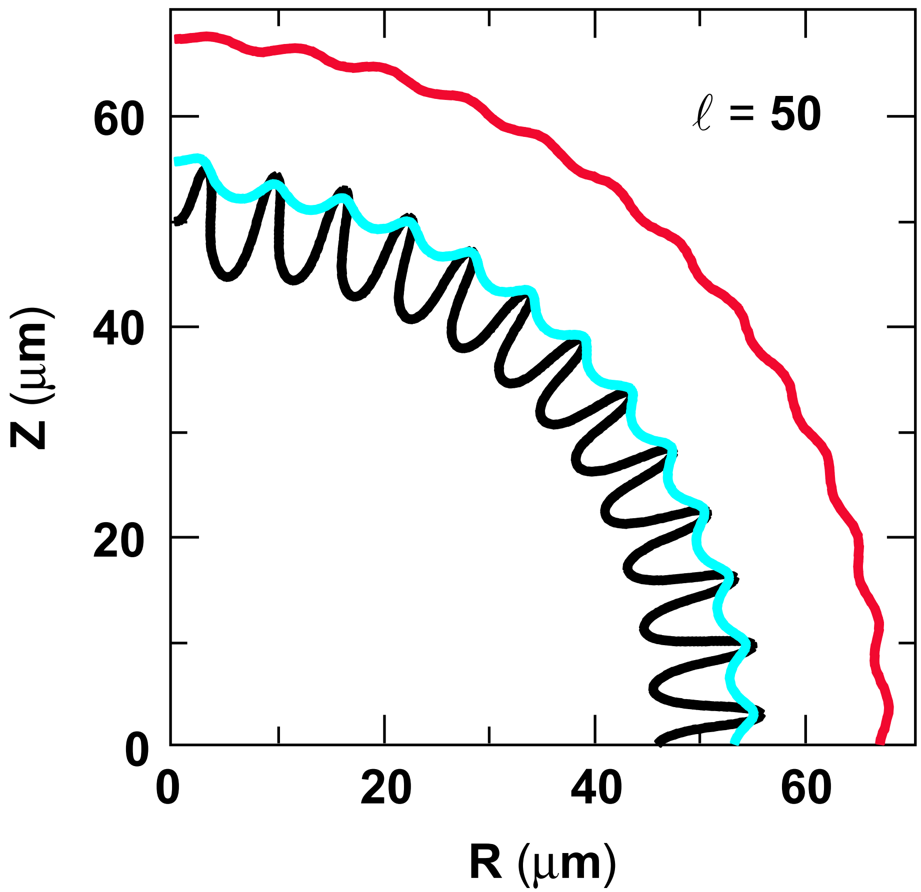
$k = \ell/R$, $R = 65\ \mu m$, $\langle g\rangle = 3100\ \mu m/ns^2$, $\langle V_a\rangle = 18\ \mu m/ns$, $\langle L_m\rangle = 1.5\ \mu m$

V. Lobatchev and R. Betti, Phys. Rev. Lett. (2000).
Betti and Goncharov, Phys. Plasmas (1998).

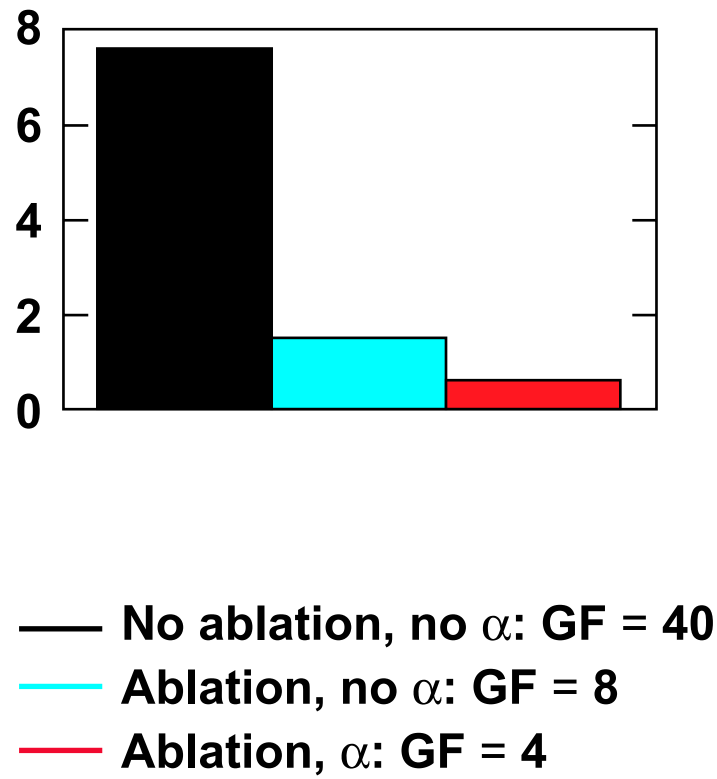
TC5769

Two-dimensional simulations show that the stabilizing effect of hot-spot ablation significantly reduces the deceleration RT growth well into the nonlinear regime

Inner shell surface at stagnation



Normalized amplitude Δ/0.1 λ



TC5770

1-D shell hydrodynamics and marginal ignition

Traditional ignition models consider the hot spot mass as constant, neglect the confinement action of the shell, and treat heat conduction as an energy loss

- Traditional model of ignition uses the stagnation energy balance

$$M_{hs}\,\dot{T} \sim \dot{W}_{\alpha} - \dot{W}_{conduction} - \dot{W}_{expansion/no\ shell} - \cancel{\dot{W}_{radiation}}$$

- Ignition requires T > 7 to 10 keV, ρR > 0.2 to 0.3 ⇒ $\dot{T} > 0$

- Hot-spot energy equation in the presence of ablation:

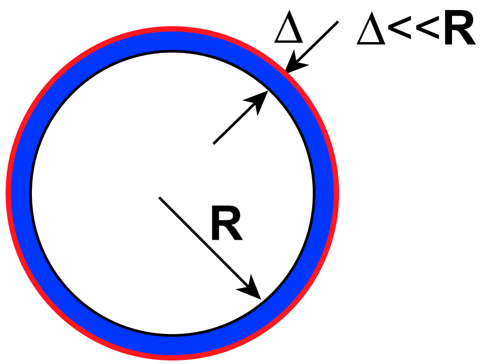
$$\frac{d}{dt}\left(PR^3\right) = \frac{5}{3}D_{\alpha}P^2R^3 - 2PR^2\dot{R}$$

Alpha heating

Decompression cooling if $\dot{R} > 0$;
PdV work if $\dot{R} < 0$

- The relation between P and R is determined by the shell.

The simplest shell model is described by an incompressible shell



- Shell Newton's law

$$M_{shell}\ddot{R} = 4\pi PR^2$$

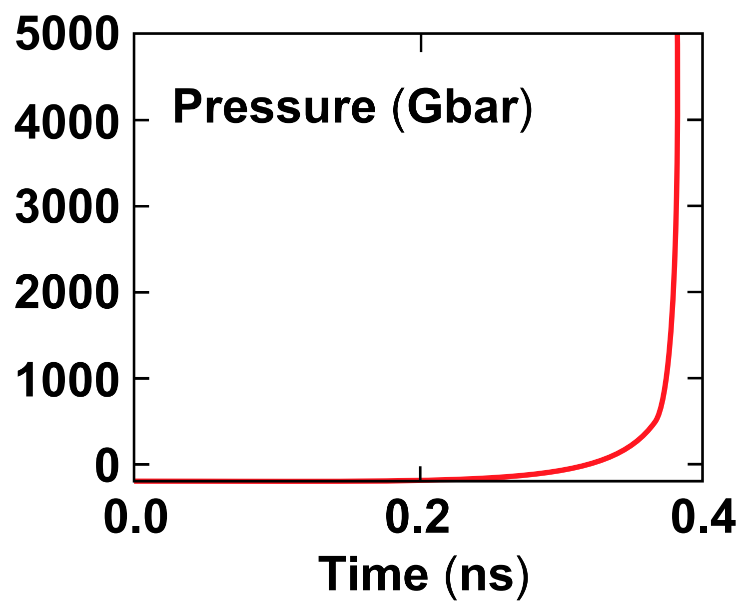
- Hot-spot energy equation

$$\frac{d}{dt}\left(PR^3\right) = \frac{5}{3}D_\alpha P^2R^3 - 2PR^2\dot{R}$$

Alpha heating

Decompression cooling if $\dot{R} > 0$;
PdV work if $\dot{R} < 0$

Definition of ignition → singular solution

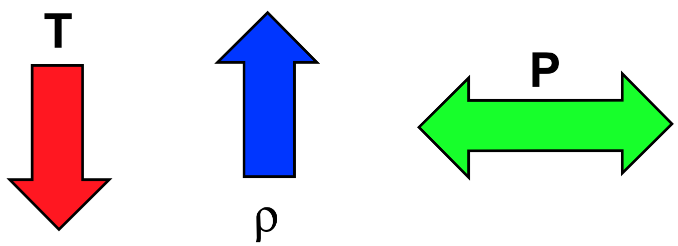


Ignition requires alpha heating > decompression cooling right after stagnation.

TC5772

If the temperature stays above ~7 keV where $\langle\sigma v\rangle \sim T^2$, ignition is not affected by heat-conduction losses

- Heat-conduction losses are recycled by mass ablation into the hot spot and do not change the hot-spot pressure.

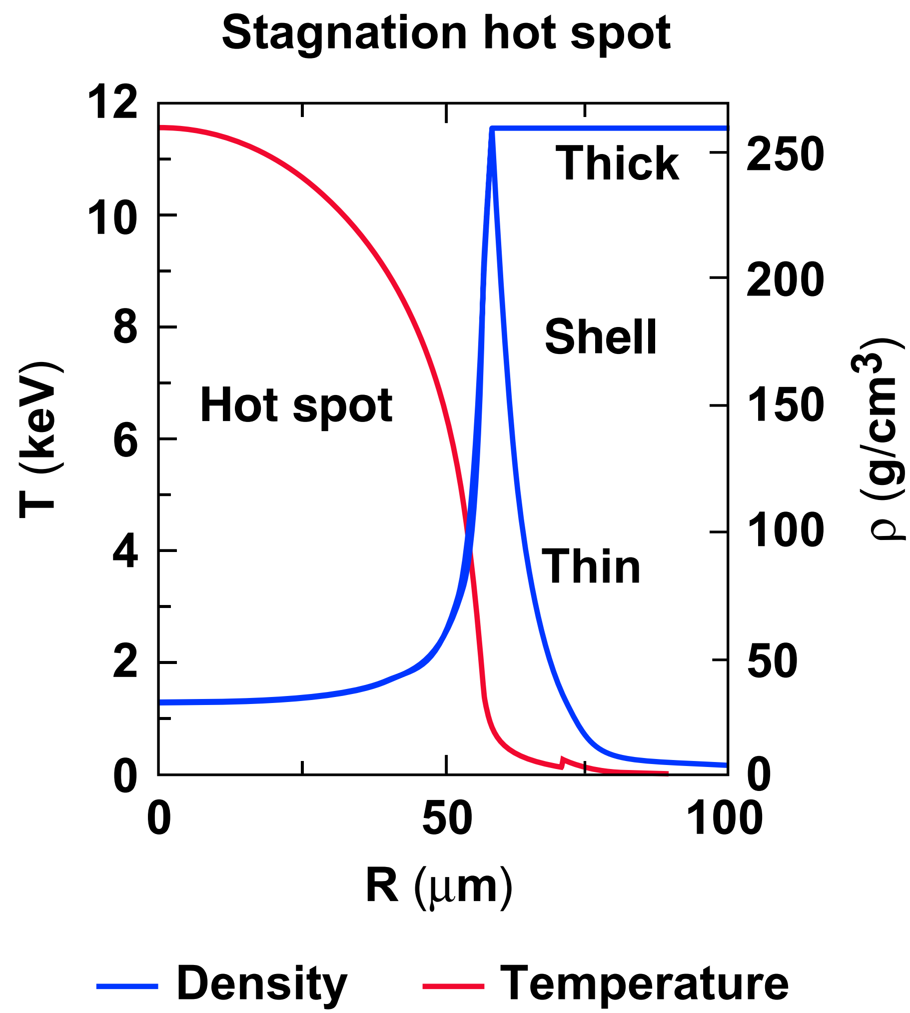


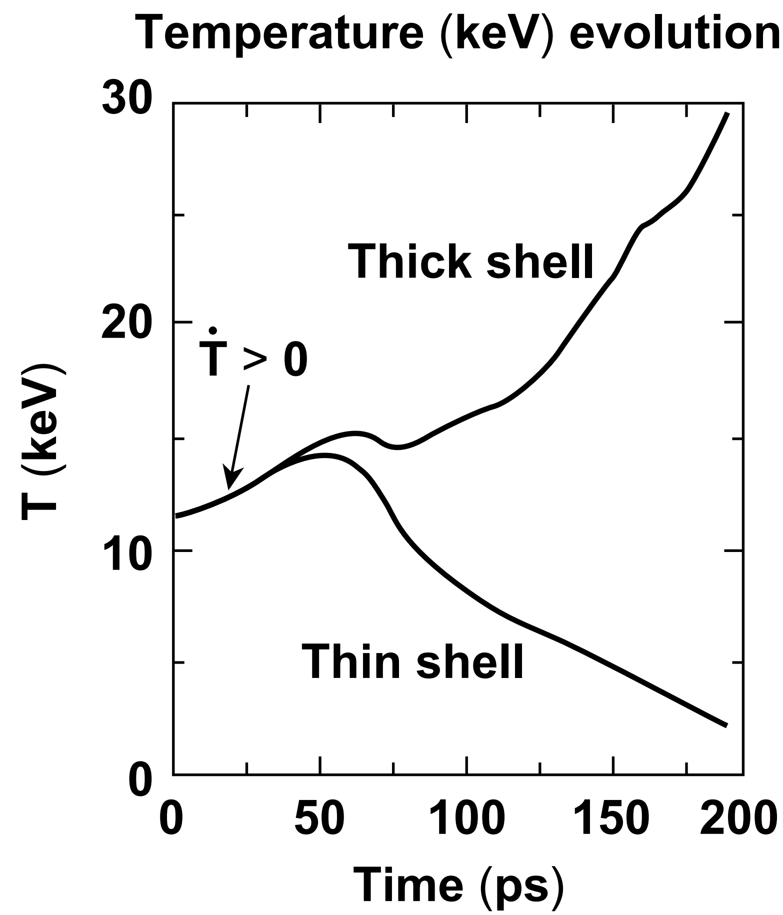
- If $T_{average} > 7$ keV, then $\langle\sigma v\rangle \sim T^2$ and the fusion rate depends only on P:

$$n^2 \langle\sigma v\rangle \sim n^2 T^2 \sim P^2$$

- Ignition is not affected by heat losses. The only energy loss is decompression cooling tamped by the heavy shell.

The shell inertia determines the ignition of the hot spot

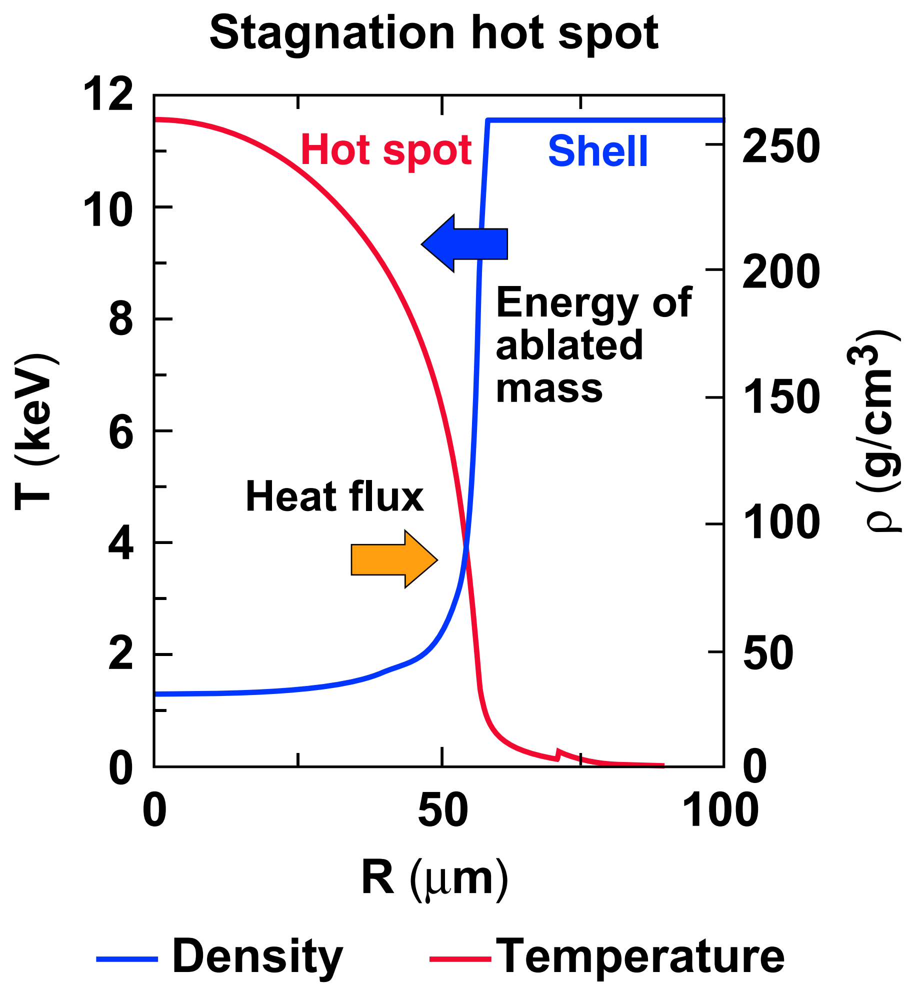


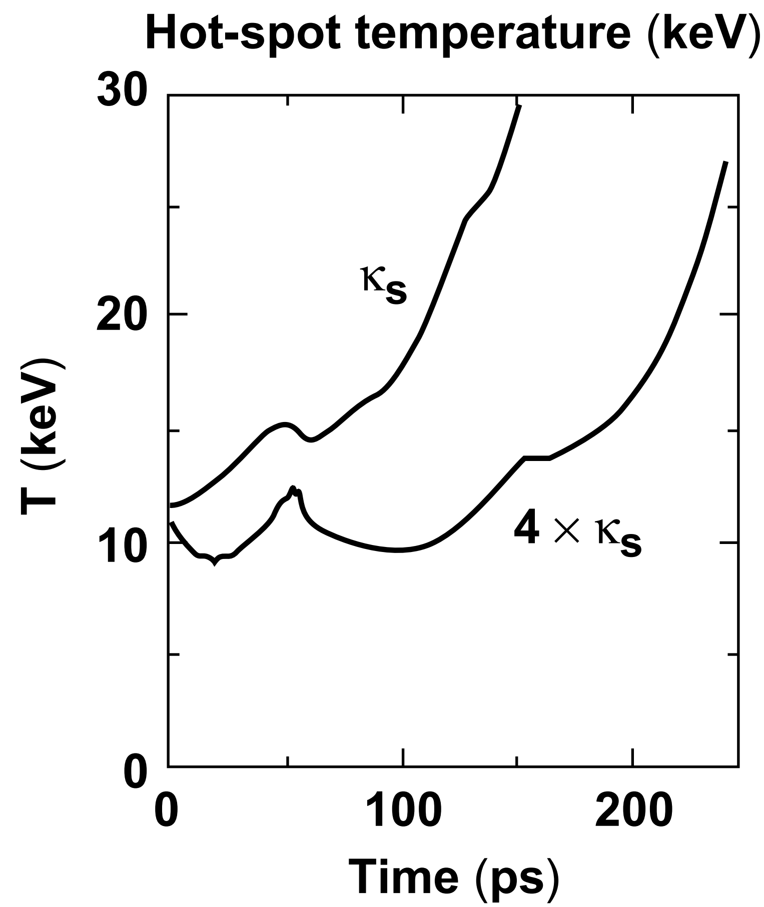


TC5773

The heavy shell recycles the heat-conduction losses through ablation

- Heat losses do not affect the hot-spot energy balance (if $\langle\sigma v\rangle \sim T^2$).





TC5774

The ignition condition from the coupled hot spot–shell model shows a threshold in kinetic energy

$$\left[\frac{\text{Alpha heating}}{\text{Decomp. cooling}}\right]_{\text{stagnation}} > 1$$

$$E_k \geq \frac{2\pi}{D_\alpha^3} \frac{\beta_0^3}{V_{imp}^7}$$

$$\beta_0 = \frac{P_{hs}^0}{\left(\rho_{sh}^0 / A_{sh}^0\right)^{5/3}}$$

E_k = shell kinetic energy

$\rho_{sh}{}^0$ = shell density

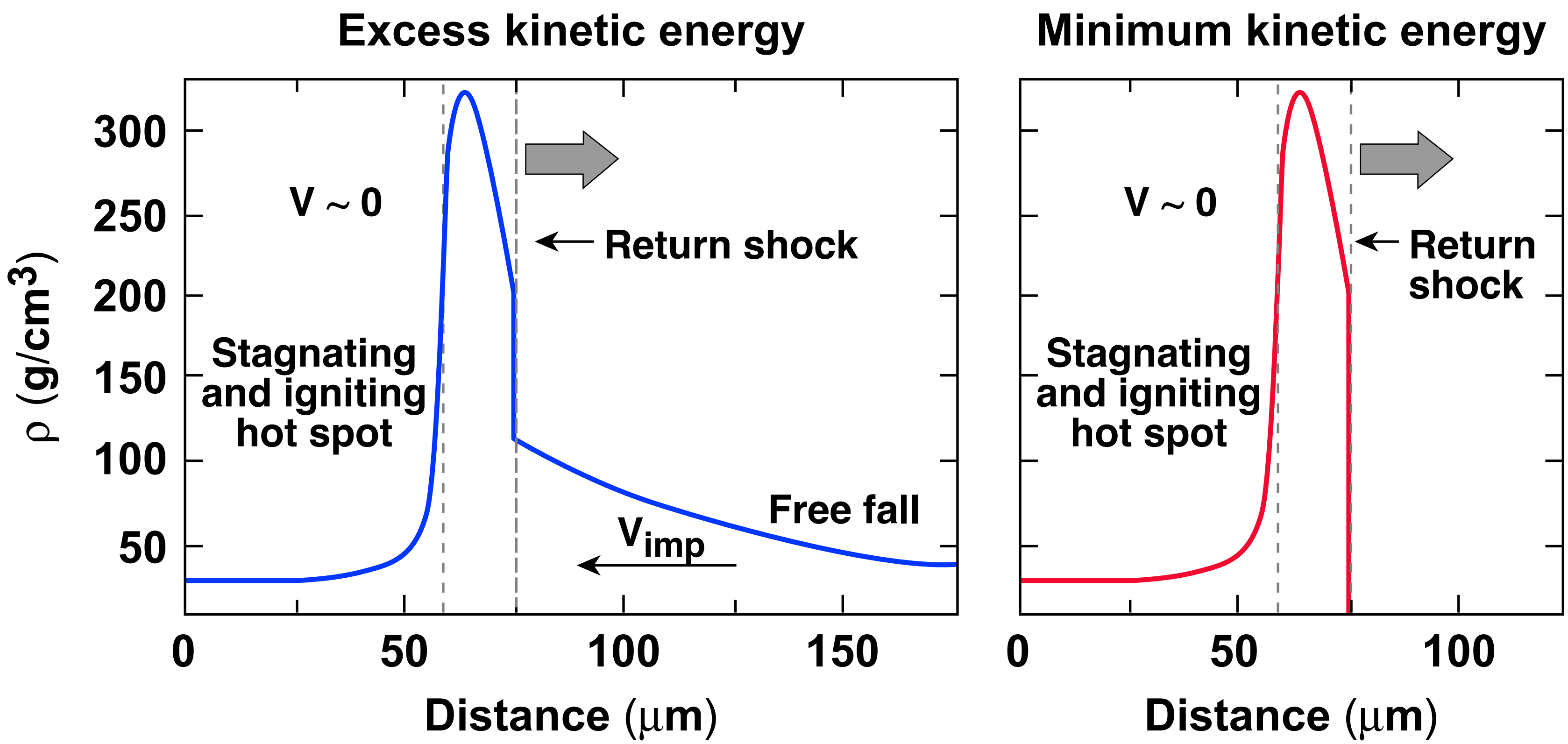
$A_{sh}{}^0$ = shell aspect ratio

V_{imp} = shell implosion velocity

$P_{sh}\,(0)$ = hot-spot pressure

<u>at the beginning of the deceleration phase</u>

Ignition with minimum kinetic energy requires that the return shock be on the outer shell surface at stagnation



- Optimum shell thickness (or aspect ratio) is such that the return shock is at the outer shell surface when the inner surface is stagnating (and the hot spot is igniting).

TC5776

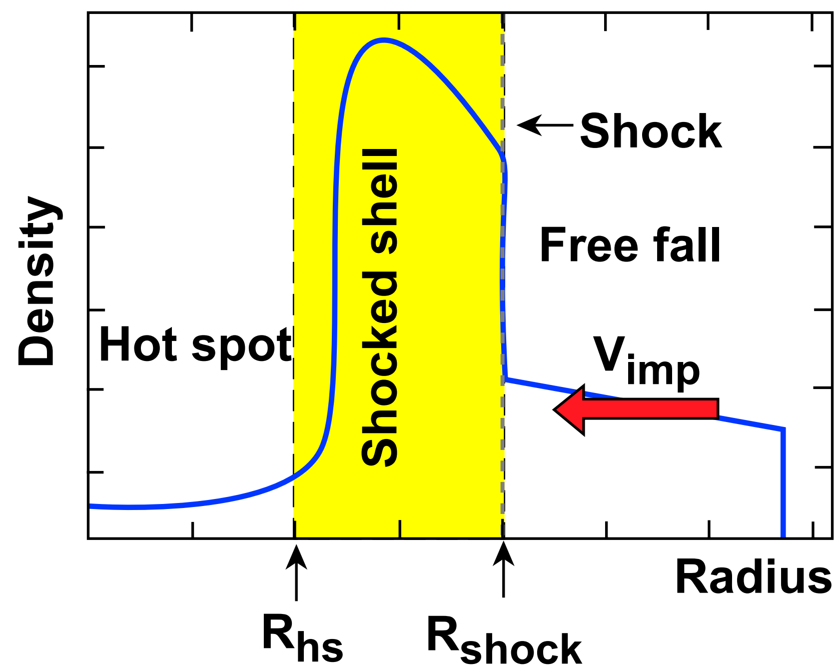
The hydrodynamics of the shocked part of the shell and hot spot is described by four coupled ODE's

$$M_{ss}\ddot{R}_{hs} = 4\pi P_{hs} R_{hs}^2 - \dot{M}_{ss} V_{imp}$$

$$\dot{M}_{ss} = 4\pi\rho_{ff} R_{shock}^2 \left(\dot{R}_{shock} + V_{imp}\right)$$

$$\dot{R}_{shock} = \frac{1}{3} V_{imp} + \frac{4}{3}\dot{R}_{hs}\frac{R_{shock}}{R_{hs}}$$

$$\frac{\dot{P}_{hs}}{P_{hs}} = -5\frac{\dot{R}_{hs}}{R_{hs}} + \frac{5}{3} D_\alpha P_{hs}$$



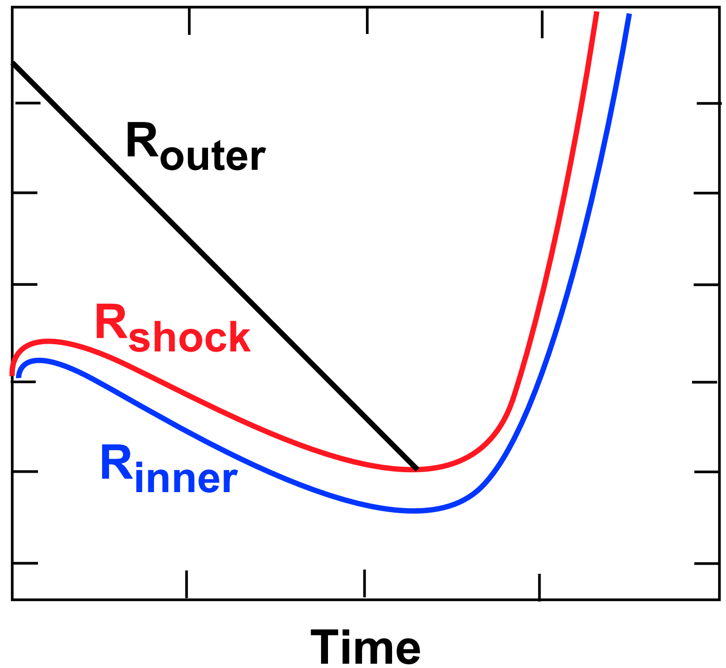
The condition of minimum energy required for ignition leads to simple relations between stagnation and initial values

$t = 0 \rightarrow$ beginning of deceleration phase (return shock interacts with the shell)

$$\rho_{shell}(stag.) \sim \rho_{shell}(0) A^2_{shell}(0)$$

$$P_{shell}(stag.) \sim P_{hs}(0) A^5_{shell}(0)$$

$$\beta_0 \equiv \frac{P_{hs}(0)}{\left[\rho_{shell}(0) / A_{shell}(0)\right]^{5/3}} \sim \frac{P_{shell}(stag.)}{\rho_{shell}(stag.)^{5/3}} \sim \alpha_{stag}$$



TC5830

Minimum energy required for ignition depends on the shell adiabat and the implosion velocity

Current model

$$E_k \geq 2.1(\mathrm{kJ})\,\alpha_{\mathrm{stag}}^{3}\left(\frac{3\bullet 10^7}{V_{\mathrm{imp}}}\right)^{7}$$

$$\alpha_{\mathrm{stag}} = 2.8\,\alpha_{\mathrm{if}}^{0.8}\left(\frac{V_{\mathrm{imp}}}{3\bullet 10^7}\right)^{0.67}\left(\frac{P_{\mathrm{shell}}}{100\,\mathrm{Mb}}\right)^{-0.13}$$

$$E_k > 59(\mathrm{kJ})\,\alpha_{\mathrm{if}}^{2.4}\left(\frac{3\bullet 10^7}{V_{\mathrm{imp}}}\right)^{5}\left(\frac{P_{\mathrm{shell}}}{100\,\mathrm{Mb}}\right)^{-0.4}$$

Herrmann, Lindl, Tabak: LASNEX code

$$E_k \geq 2.7(\mathrm{kJ})\,\alpha_{\mathrm{stag}}^{2.66}\left(\frac{3\bullet 10^7}{V_{\mathrm{imp}}}\right)^{7.2}$$

$$\alpha_{\mathrm{stag}} = 3.2\,\alpha_{\mathrm{if}}^{0.75}\left(\frac{V_{\mathrm{imp}}}{3\bullet 10^7}\right)^{0.44}\left(\frac{P_{\mathrm{shell}}}{100\,\mathrm{Mb}}\right)^{-0.21}$$

$$E_k > 50(\mathrm{kJ})\,\alpha_{\mathrm{if}}^{1.9}\left(\frac{3\bullet 10^7}{V_{\mathrm{imp}}}\right)^{5.9}\left(\frac{P_{\mathrm{shell}}}{100\,\mathrm{Mb}}\right)^{-0.77}$$

Herrman *et al.,* Nucl. Fusion 41, 99 (2001).

Other scaling laws show similar trends though the physics is quite different

Basko, analytical (including heat losses) + DEIRA code

$$E_k \geq \alpha^3 \left(\frac{3 \bullet 10^7}{V_{imp}} \right)^7 \psi_E \qquad 1.5 < \psi_E\left(R_{hs} / R_{shell}\right) < 10^3$$

Kemp, Meyer-ter-Vehn, Atzeni (self-similar return shock)

$$\alpha_{stag} \sim \alpha_{if} \mathrm{Mach}^{1/2} \sim \alpha_{if}^{0.85} V_{imp}^{0.5} P_{shell}^{-0.1}$$

$$E_k \sim \left(\rho_{hs} R_{hs} T_{hs}\right)^3 \alpha_{if}^{1.8} \frac{P_{shell}^{-0.8}}{V_{imp}^6}; \qquad \text{If } \rho_{hs} R_{hs} T_{hs} \sim V_{imp} \Rightarrow E_k \sim \alpha_{if}^{1.8} \frac{P_{shell}^{-0.8}}{V_{imp}^3}$$

Basko *et al.,* Nucl. Fusion 35, 87 (1995);
Kemp, Meyer-ter-Vehn, Atzeni *et al.,* Phys. Rev. Lett. 86, 3336 (2001).

The stagnation ρR indicates that the α particles are confined within the hot spot

$$\left\langle T_{hs}^{stag.} \right\rangle \sim \frac{V_{imp}^{4/7}}{\kappa_0^{2/7}} \approx 7\,\text{keV}\left(\frac{V_{imp}}{3 \bullet 10^7}\right)^{4/7} \Rightarrow V_{imp} \geq 3 \bullet 10^7$$

$$\left[\rho R\right]_{hot\ spot}^{stag.} \sim \kappa_0^{2/7} V_{imp}^{3/7} \approx 0.2\ \text{g/cm}^2 \left(\frac{V_{imp}}{3 \bullet 10^7}\right)^{3/7} \Rightarrow \left[\rho R\right]_{hot\ spot}^{stag.} \geq 0.2$$

$$\rho_{hs} R_{hs} T_{hs} \sim V_{imp}$$

Alpha heating > decompression cooling

Local alpha deposition

$\Rightarrow \rho R_{hot\ spot} \geq 0.2$

Basko *et al.,* Nucl. Fusion 35, 87 (1995);
Kemp, Meyer-ter-Vehn, Atzeni *et al.,* Phys. Rev. Lett. 86, 3336 (2001).

Mass ablation off the shell into the hot spot changes the classical picture of ICF ignition and deceleration-phase RT instability

- **Balancing the alpha heating and the decompression cooling (including the shell inertia) seems to explain the LASNEX marginal ignition scaling.**

- **The heat losses do not enter into the stagnation hot-spot energy balance as they are recycled into the hot-spot by mass ablation off the shell (as long as $\langle \sigma v \rangle \sim T^2$).**

- **The conduction losses determine only the implosion velocity required to enter into the regime where $\langle \sigma v \rangle \sim T^2$.**

- **Mass ablation off the shell leads to a cutoff in the spectrum of the deceleration-phase Rayleigh–Taylor instability. For a direct-drive NIF-like capsule, the cutoff wave number occurs at $\ell \approx 90$.**