INTRODUCTION TO INERTIAL CONFINEMENT FUSION

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Lecture 26

Status of ICF and remaining issues
Indirect Drive, Symmetric Direct Drive and Polar Direct Drive

Direct-drive target

Capsule

Laser beams

OMEGA
30 kJ, 30 TW

Indirect-drive target

NIF
2 MJ, 500 TW

Polar direct drive

(a)
Achieving ignition requires control of hydrodynamic and laser–plasma instabilities, low-mode asymmetries and the impact of engineering features.

Engineering features
- Fill tube
- Tent

Low-mode asymmetries

Laser imprinting
- Laser $t = 0$

Laser–plasma instabilities (CBET, SRS, SBS, TPD)

- CBET: cross-beam energy transfer
- SRS: stimulated Raman scattering
- SBS: stimulated Brillouin scattering
- TPD: two-plasmon decay

Surface defects
- Stalk

Center-beam ray
- $n_e/4$ TPD
- Hot electrons

Edge-beam ray

Capsule instability

$\uparrow$ SBS: stimulated Brillouin scattering
$\uparrow \uparrow$ TPD: two-plasmon decay
Simulations evaluate degradation mechanisms

Low foot 4-shock design N120321

<table>
<thead>
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<th>Degradation mechanism</th>
<th>Sym.</th>
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<th>Tent only</th>
<th>All 2-D effects</th>
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High foot 3-shock design N120321

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Laser pulse shapes and target specifications are the knobs we can easily turn.
Advances in indirect drive ICF at the National Ignition Facility

Low Foot $\rightarrow$ High Foot $\rightarrow$ HDC/BF + low-gas-fill hohlraum

What is next?

- Maximize implosion scale
- Maximize coupled energy
- Maximize laser energy
- NIF demonstrated 2.1 MJ (at 430 TW) in June 2018

O Hurricane, presented at the 19th International Congress on Plasma Physics, Vancouver, BC, 4–8 June 2018;
Changes in pulse shapes led to larger improvements in performance

O. Hurricane et al, Nature 2014

The high foot pulse sets the shell on a higher adiabat/isentrope because it launches a stronger shock in the foot of the pulse.
Also direct drive implosions are thought to have severe hydro-stability limitations at low adiabat and/or high IFARs and low ablative stabilization of the RT

- Mixing front from imprint travels distance $h \sim \beta gt^2 \sim \beta R_0$, and fraction of shell comprised

$$= \frac{h}{\Delta} = \frac{\beta R_0}{\Delta} = \beta \text{IFAR}$$

$\gamma_{\text{exp}} \sim \frac{1}{\text{IFAR}^{1.2}}$

$\rho R_{\text{exp}} \sim \frac{1}{\text{IFAR}^{0.5}}$

3D Aster simulations with laser imprinting

Lowest IFAR = 17

Highest IFAR = 44

Igumenshchev (LLE), private communication (2018)
High-foot growth-factor calculations and simulations are consistent with the expectation of less instability.

Hurricane et al, 2013
The performance of direct drive capsules is also degraded by Cross Beam Energy Transfer (CBET)

- CBET involves electromagnetic (EM)-seeded, low-gain stimulated Brillouin scattering
- EM seed is provided by edge-beam light
- Center-beam light transfers some of its energy to outgoing light
- The transferred light bypasses the highest absorption region near the critical surface

CBET reduces laser absorption and hydrodynamic efficiency.

Other laser-plasma instabilities (SRS, SBS, TPD) are also limiting performance but likely to a lesser extent. However suppressing those instabilities may open up a much more attractive portion of parameter space for laser fusion at higher laser intensities

- The monochromatic laser light can parametrically excites the two waves in the plasma: the electron plasma wave and the ion acoustic wave

\[ \bar{k}_L = \bar{k}_1 + \bar{k}_2 \]

- The three main instabilities satisfy the resonance conditions \[ \omega_L = \omega_1 + \omega_2 \]

- 1 and 2 refer to either EM or electron plasma or ion acoustic waves, \( L \) refers to the incident laser

- Stimulated Raman Scattering: laser decays into an EM light wave and a Plasma Wave. The largest growth rate is for a backscattered light wave \[ \rightarrow \] reflects the laser

- Stimulated Brillouin Scattering: laser decays into a EM light wave and a Ion Acoustic Wave. The largest growth rate is for a backscattered light wave \[ \rightarrow \] reflects the laser

- Two Plasmon Decay: laser decays into two plasma waves \[ \rightarrow \] \( \omega_L = 2\omega_{pe} \)
Plasma waves excited by laser-plasma instabilities accelerate electron and can preheat the target (increasing the adiabat)

- Electrons with velocity close to the phase velocity of the electron plasma wave can be accelerated like a surfer is accelerated by an ocean wave.
- The Two-Plasmon Decay (TPD) occurs near the quarter critical density to satisfy
  \[ \omega_{pe} = \frac{\omega_L}{2} \]
- SRS and SBS occur at lower densities in the corona and are not localized like the TPD.
- Since SRS excites electron plasma waves, it can accelerate electrons and preheat the shell.
- Both SRS and SBS reflect laser light and decrease energy coupling to the shell.
Alpha heating and burning plasmas are intermediate milestones along the path to ignition; ICF ignition needs to be defined.

- **Alpha heating**:
  - Deuteron
  - Triton
  - Fusion reaction
  - Alpha heating of plasma increases temperature and reaction rate
  - Alpha particle (3.5 MeV)
  - Fast neutron (14.1 MeV)

- **Fusion plasma**

- **Equation**:
  \[ Q_\alpha = \frac{W_\alpha}{W_{\text{ext}}} \]

**Burning plasmas**

- \( Q_\alpha > 1 \)

**Ignited plasmas**

- \( Q_\alpha \gg 1 \)
Alpha heating and ignition metrics are related to the Lawson criterion. Areal density and yield determine proximity to ignition.

\[ f_\alpha = \frac{1}{2} \frac{E_\alpha}{E_{HS}} \sim \frac{p^2 \langle \sigma v \rangle}{\frac{T^2}{2} T} \sim \frac{P_T}{\langle \sigma v \rangle} \sim \rho R^{0.8} T^{1.6} \sim \rho R_{tot}^{2/3} \left( \frac{Yield}{Mass_{DT}} \right)^{1/3} = \chi_\alpha \]

\( f_\alpha \) and \( \chi_\alpha \) are used to measure alpha heating.

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* R. Betti et al., Phys. Rev. Lett. 114, 255003 (2015);
A. R. Christopherson et al., Phys. Plasmas 25, 012703 (2018);
Alpha-heating metrics are currently used to quantify the yield amplification caused by the alpha feedback on fusion reactivity.

The constant 0.05 was used to adjust the scale to $f_\alpha$.

\[ f_\alpha \equiv \frac{1}{2} \frac{P_\alpha}{E_{HS}} \]

\[ \chi_\alpha \equiv \rho R^{0.6} \left( \frac{0.05 \text{ Yield}_{16}}{M_{DT}^{\text{stag}}} \right)^{0.34} \]

Ignition is the transition from rapidly growing alpha heating within the hot spot to burn propagation in the shell.

Fusion energy output for ignition depends on the target:
- Roughly indirect-drive ignition: $\sim 300$ to $800$ kJ
- Roughly direct-drive ignition: $\sim 1.5$ to $3.5$ MJ

Yield depends on burnup fraction: $\theta_{\text{burnup}} \approx \frac{\rho R}{\rho R + 7}$

Ignition requires yield amplifications of 15-25.

\[ f_{\alpha} \equiv \frac{1}{2} \frac{E_{\alpha}}{E_{\text{HS}}} \]
Improved performance of NIF indirect-drive implosions was achieved by hydro instability mitigation, symmetry control, and enhanced coupling.

Low-foot → **improve stability** → High-foot → **better coupling, control symmetry** → HDC/BF + low-gas-fill (LGF) hohlraum
The “no\(\alpha\)” metrics provide a better measure of the proximity to ignition in terms of pure hydrodynamic performance. A \(\sim 50\%\) increase in Lawson parameter is required for both indirect drive and hydro-scaled direct drive.

\[ \chi_{\text{no}\alpha} = \left[ \frac{P\tau}{\rho R^{0.6}} \right]_{\text{no}\alpha} \sim \left( \frac{Y_{\text{no}\alpha}}{M_{DT}} \right)^{0.34} \]

Not easy but not out of reach!