Advanced Target Designs for Direct-Drive Inertial Confinement Fusion

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Summary

Improved-stability, high-gain designs are considered for direct-drive ICF

- Direct drive offers the possibility of significantly higher gains than indirect-drive ICF.

- New designs show significant improvements in shell stability and target gain.

- Such designs implement adiabat shaping and foams wicked with DT.

- The possibility of performing direct-drive ignition experiments in NIF’s x-ray drive configuration (polar direct drive) is currently being considered.
A standard “all-DT” ignition design consists of a DT-ice layer overcoated with a thin polymer layer.
There are several disadvantages in using an “all-DT” design

- **Advantages**
  - Simplicity of the design
  - Easy to tune (need to control one shock and one compression wave)

- **Disadvantages**
  - Marginal shell stability (severe constraints on laser smoothing)
  - Low laser absorption (60% for NIF and 40% for OMEGA)
  - Moderate yields
Shell stability and compressibility depend on the adiabat

- Minimum energy required for ignition: $E_{\text{min}} \sim \alpha^{1.88}$
  \[ \alpha = \frac{P}{P_{\text{Fermi}}} \]
- Rayleigh–Taylor instability growth $\gamma = \alpha_{RT}(kg)^{1/2} - \beta_{RT}kV_a$
  \[ V_a \sim \alpha^{3/5} \]

\[ \alpha \text{ of ablated mass can be increased without affecting } E_{\text{min}} \]

Stability of direct-drive targets can be substantially enhanced using adiabat shaping

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\( \alpha = 3 \) picket-pulse target designs are considered for the NIF and OMEGA.

NIF

- CH, 17 \( \mu \)m
- DT ice
- DT gas
- 1.7 mm

\( t_p = 200 \) ps
\( P_{\text{max}} = 400 \) TW
\( \rho R_{\text{max}} = 1.45 \) g/cm\(^2\)
\( Y = 3 \times 10^{19} \)
\( \text{Abs} = 80\% \)

OMEGA

- CH, 5 \( \mu \)m
- DT ice
- DT gas
- 430 \( \mu \)m

\( t_p = 50 \) ps
\( P_{\text{max}} = 25 \) TW
\( \rho R_{\text{max}} = 300 \) mg/cm\(^2\)
\( Y = 6 \times 10^{14}; \text{ Abs} = 57\% \)

A potential target for polar direct drive
Multimode *ORCHID* simulations demonstrate better stability of the shaped-adiabat design.

Imprint simulations: \( \ell = 2–200 \), DPP + PS, 1-THz SSD; OMEGA design

Shell is significantly less distorted in the picket design.
Both NIF and OMEGA picket designs are predicted to stay intact during the acceleration phase.

- 1-THz, 2-D SSD; 80-nm outer-surface roughness; 1-μm inner-ice roughness
- The bubble amplitude is calculated using the stability postprocessor.\(^1\)

2-D ORCHID simulations of an OMEGA target show higher nonuniformity levels in the relaxation design.
Mode decomposition reveals enhanced high $\ell$-mode amplitudes in the relaxation design.

- Beginning of acceleration (imprint amplitudes)
- Acceleration phase ($\Delta R_a = 70 \, \mu m$)
High $\ell$-mode enhancement is due to early-time Rayleigh–Taylor growth
A surrogate foam target is proposed to mimic conditions of the cryogenic designs.

- Cryogenic targets cannot be routinely used to study details of implosion.

Requirements for a surrogate:

1. Design should capture early RT growth.
   - Density ratio overcoat/foam = 3 to 4
   - Overcoat thickness 3 to 5 μm

2. Adiabat shaping is not compromised by radiation from corona (\( ρ < 500 \text{ mg/cc} \), restrictions on high-Z constituents).

3. No additional instabilities are created (\( ρ > 150 \text{ mg/cc} \)).
   - An unstable radiation ablation front is created in low-density foams.

The optimal foam density is 180 to 250 mg/cc.
Adiabat shaping is compromised by coronal radiation in CH shells

At the shock breakout

End of acceleration phase

Mass (mg)

Density (g/cc)

No picket

Picket

Adiabat (arbitrary units)

Mass (mg)
Adiabat shaping is maintained throughout the implosion in 200-mg/cc foam design

\[ Y = 1.7 \times 10^{11} \text{ for 15-atm-D}_2 \text{ fill, } \rho R_{\text{total}} = 166 \text{ (no picket), 162 (picket) mg/cm}^2 \]
Multimode *DRACO* simulations indicate greater shell stability in the picket design.

OMEGA foam target (200 mg/cm$^3$) with 5-μm-CH overcoat (modes 2 to 200; 1-THz, 2-D SSD with PS)
High-gain “wetted foam” designs have been considered for the NIF.

**Polyimide, 3 µm**

- **A**
  - CH (DT)$_{20}$
  - 173 µm
  - DT ice
  - 280 µm
  - 1.9 mm

- **B**
  - CH (DT)$_{4}$
  - 173 µm
  - DT ice
  - 260 µm
  - 1.8 mm

**G** = 124

- $V_{\text{imp}} = 3 \times 10^7$ (cm/s)
- $\rho R_m = 1.7$ g/cm$^2$
- Abs = 85%

**G** = 82

- $V_{\text{imp}} = 3.9$
- $\rho R_m = 1.5$
- Abs = 86%

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**Graph**

- **Power (TW)**
- **Time (ns)**

- $\alpha = 2$

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The possibility of performing direct-drive ignition experiments in NIF’s x-ray drive configuration (polar direct drive) is currently considered\(^1\)

\[\sigma_{\text{rms}} = 0.9\% \quad n = 2.5 \text{ beams}\]

At \(t = 0\) with 100\% absorption
- \(\bigcirc\) NIF x-ray drive beam ports
- \(\bullet\) 48 beam direct-drive directions

\(^1\) See W03 by R. S. Craxton.
Angular-dependent pulse shaping and target shimming are considered to achieve implosion symmetry.
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