Inertial Confinement Fusion, High Energy Density Plasmas and an Energy Source on Earth

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This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.
We are making good progress toward achieving fusion ignition and high gain for energy applications

- Recent design innovations have dramatically improved the robustness of inertial confinement fusion (ICF) targets
- Target designs exist that produce gain adequate for energy applications
- A wide variety of qualitatively different designs can be tested at the National Ignition Facility (NIF)
- NIF is scheduled for completion by 2009
  - Physics experiments have already begun
Inertial Fusion Energy power plants have 4 parts

Driver
To heat and compress target to fusion conditions

Driver options:
- Laser (DPSSL or KrF)
- Heavy Ions
- Z-pinch

Target Factory
Needs to produce low cost targets rapidly

Fusion chamber
Extract energy from target explosions and breed tritium

Steam plant to convert fusion heat into electricity
Target designs can be characterized by ignition method, compression method and driver.

**Driver**
- Laser
  - $\eta = 5\text{-}10\%$
- Heavy ion Accelerator
  - $\eta = 15\text{-}40\%$
- Z-pinch
  - $\eta \approx 15\%$

**Compression**
- Direct drive
- Indirect drive

**Ignition**
- Fast Ignition
- Ignition by stagnation of convergent flow

These schemes can be tested at the NIF.
The inertial confinement process

- X-rays or driver beams heat ablator
- Rocket reaction implodes fuel shell
- Fuel shell stagnates
- Ignition begins
- Burn propagates to compressed outer fuel
- Yield is produced
Technology advances have made innovative concepts possible: ultra-high brightness lasers may allow a fundamentally new method of igniting inertial fusion capsules.

**Conventional ICF**

- Shock heated central spot ignites a high density cold shell
  \[ P_{HS} = P_c = \alpha \rho_c^{5/3} \]

**Fast Ignitor**

- Fast-e− heated side spot ignites a lower density, larger uniform fuel ball
  \[ P_{HS} \gg P_c \]


**Advantages of Fast Ignitor**

- Fast Ignitor implosions are less stressing: (mix, convergence, ...)
- Lower \( \rho \) \( \Rightarrow \) more mass to burn \( (E_c = \alpha M_c \rho_c^{2/3}) \) \( \Rightarrow \) Higher Gain

**Significant R&D is required to explore potential of this concept**
ICF ignition requires large energy and power densities

\[
\log_{10}(\text{Energy density (J/cm}^3)) \quad \log_{10}(\text{Density (gm/cm}^3))
\]

\[
\log_{10}(\text{Power density (W/cm}^3))
\]

- Focused short pulse laser
- Robust burn
- ICF ignition
- Planar shock
- Convergence + stagnation
- Implosion
- MFE
- Supernova core
Achieving the necessary multiplication of power, energy and mass densities requires a well controlled implosion.

- The fuel must be driven with a well timed sequence of weak shocks so that its entropy is minimized.
- The pressure must be symmetrically applied.
- Hydrodynamic instabilities must be mitigated.
Implosion symmetry is an important issue for high convergence ratio targets

Typical convergence ratios >30 require $\frac{\delta v}{v} \sim 1\%$ so converged $\frac{R}{R} < 1/2$

60 beams is adequate for directly driven targets
Radiation symmetry in indirectly driven targets is controlled by three factors:

1. Hohlraum re-radiation smoothes wall flux by number of reemissions before absorption.
2. Wall to capsule transport smoothes high $l$ modes.
3. Appropriate location of beam spots eliminates low order modes.

Relative flux variation at capsule vs. $R_{\text{case}}/R_{\text{capsule}}$ for different spherical harmonics ($P_2$, $P_3$, $P_4$, $P_6$).
We are using internal hohlraum shields to develop distributed radiator targets with larger beam spots.

- Shine shield to control $P_2$
- Radiation shim to control early time $P_4$

**Beam spot:** 3.8 mm x 5.4 mm  
**Effective radius:** 4.5 mm  
**6.7 MJ beam energy**  
**Gain = 58**

**Beam spot:** 1.8 mm x 4.1 mm  
**Effective radius:** 2.7 mm  
**5.9 MJ beam energy**  
**Gain = 68**

66% increase in beam radius with a 14% increase in beam energy.

Callahan-Miller 7/00
The ablation front hydrodynamic instability can destroy an imploding shell.

1. Ablation front RT Growth dominates Instability growth
2. Feed through and initial roughness seeds inner surface Perturbations
3. Inner surface seeds grow on deceleration

Growth starts from surface or other shell variations

X-rays or laser
Hydrodynamic instabilities can be mitigated by design choices

- Appropriate choice of ablator materials
- Appropriate choice of pulse shape
New designs using Be with graded Cu dopant are spectacularly robust

Be next to fuel is clean, dopant rises to max in two steps and back down again

CH surface finish achieved in laboratory: 20±5 nm

For short wavelength RT, this capsule can tolerate a roughness 30 times greater than typical CH capsules produced in the laboratory => IFE targets driven with low intensity laser or ion beams
Baseline ignition target has been redesigned using 3D code Hydra, and simulated with full asymmetry + capsule perturbations.

Hohlraum simulations use 15 million Monte Carlo photons,
1200 rays/beam laser raytrace
NLTE, Arbitrary Lagrange Eulerian grid motion
Hohlraum redesigned — LEH liner, gas fill, cone-to-cone ratio, pointing

Capsule simulations use 12.8 million zones, 120 processors. Include intrinsic drive asymmetry, full spectrum of contributing capsule perturbations \( l \geq 2 \).
Yield 22 MJ (versus clean 24 MJ)
Through Innovative Laser Pulse Shaping we have Significantly Improved the Stability of High-Gain Direct-Drive Targets for Inertial Fusion Energy

Yield 350MJ

$E_{\text{laser}}$ 2.9MJ

Gain 120

Shell breakup fraction:
- Standard pulse ~1.8
- Picket pulse ~0.15
Fast Ignition results from ILE, Osaka are encouraging.

Light propagates down cone axis and couples near tip producing relativistic electrons.

Electrons couple to compressed fuel.

Infer 15-25% coupling efficiency from laser to compressed fuel!
Target designs with varying degrees of risk provide adequate gain for all driver concepts.
The National Ignition Facility (NIF), a nominally 1.8MJ/500TW blue laser being built at Livermore, meets the requirements for ignition.
Support infrastructure is completed in laser Bay 1
Planned deployment of additional NIF laser beams

- Full NIF (Ignition: end FY10)
  - more inner beams
  - better symmetry

- 4-fold, 2-cone symmetry

- 8-fold 2-cone symmetry

- 4-quad vert. DD planar

- 12-quad halfraums

- 10-quad halfraums

- Early quad

- Full bundle

- 6-quad DD planar

- 1st cluster

Timeline:
- FY03
- FY04
- FY05
- FY06
- FY07
- FY08
- FY09
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