Inertial Fusion Energy using Shock Ignition

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Congresso SIF, Pisa, 2014
Summary

• Shock ignition concept

• Progress in target design
  - scaling
  - defining and measuring “safety” margins
  - increasing margins (i.e. robustness)

• Conclusions & directions for future work
the standard ICF approach: *central ignition*
imploding fuel kinetic energy converted into internal energy
and concentrated in the centre of the fuel

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1) irradiation
   driver beams
   shell-target
   ablated plasma

2) implosion driven by ablation

3) central ignition

4) burn and explosion
   exploding fuel

implosion velocity for ignition:
\[ u_{\text{imp}} > 300 - 400 \text{ km/s} \]
depending on the fuel mass and on the compressed fuel in-flight isentrope:
\[ u_{\text{imp}} \propto m^{-0.15} \alpha_{\text{if}}^{2/9} \]
NIF point design:
\[ u_{\text{imp}} = 370 \text{ km/s} \]

(see, e.g., S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion, Oxford University Press, 2004.)
Standard central ignition: capsule energy decreases strongly with increasing implosion velocity

\[ E_{\text{cap}} \propto u_{\text{imp}}^{-6} \alpha_{\text{if}}^{1.8} P_{\text{abl}}^{-0.8} \] (*)

but issues as the velocity increases

- higher velocity \( \Rightarrow \) higher driving pressure \( \Rightarrow \) higher laser intensity
  \( \Rightarrow \) laser-plasma instabilities (LPI)

- higher velocity \( \Rightarrow \) hydrodynamic instabilities more dangerous

[Also, central ignition \( \Rightarrow \) isobaric compressed assembly; lower gain than from non-isobaric configurations]

(*) Herrmann, Tabak, Lindl, Nucl. Fusion 41, 99 (2001)
Pressure at stagnation is a strong function of the implosion velocity $p \sim u_{\text{imp}}^3$. 

Graph showing the relationship between stagnation pressure $p_{\text{stagn}}$ (in Tbar) and implosion velocity $u_{\text{imp}}$ (in km/s). The graph includes data points for different masses $m_{\text{imp}}$ and values of $\alpha_{\text{if}}$. The correlation line is $u_{\text{imp}}^3$. 

- $m_{\text{imp}} = 0.28$ mg, $\alpha_{\text{if}} = 1.2$
- $m_{\text{imp}} = 2.07$ mg, $\alpha_{\text{if}} = 1.2$
- $\alpha_{\text{if}} = 2$
- $\alpha_{\text{if}} = 2.4$
... but stagnation pressure can be amplified by a **properly tuned shock**

---

a) pulse generates imploding shock

b) imploding shock amplified as it converges

c) imploding shock progresses, while shock bounces from center

d) the two shocks collide, and launch new shocks; the imploding shock heats the hot spot
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Shock ignition

vs

conventional direct-drive central ignition
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![Diagram showing layers labeled as ablator, cryogenic DT, and DT vapor, with a graph showing laser power over time with a standard pulse indicated.]
Shock ignition

vs

conventional direct-drive central ignition
Shock ignition vs conventional direct-drive central ignition

Diagram showing the layers of ablator, cryogenic DT, and DT vapor, along with a graph showing Laser Power over Time, with markers for SI compression pulse, Standard pulse, and A-s picket.
Shock ignition vs conventional direct-drive central ignition

Laser Power

Time

Ignition spike
SI compression pulse
Standard pulse
A-s picket
Shock ignition of the HiPER baseline target

- Implosion velocity \( u_i = 280 - 290 \text{ km/s} \)
- \( <\alpha> = 1.2 \)
- Hydro absorption efficiency = 7% (compression pulse)
- \( <\rho R> = 1.5 \text{ g/cm}^2 \) (compression pulse only)
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Two parameters to be adjusted to achieve ignition: implosion velocity and laser spike power

--- design flexibility

for the HiPER target gain contours in the (implosion velocity – spike power plane)
scaling to higher energy $\Rightarrow$ flexibility and reduced risks

a) scaling at constant implosion velocity

- maximum laser intensity decreases with target scale
- peak intensity decreases with target scale; large enough targets ignite without spike driven shock

b) scaling at fixed ratio \( u_{\text{imp}} / u_{\text{ig}^*} \)

- velocity decreases with size; higher spike power; lower compression power
- **very high gain:** \( G > 200 \) at 2 MJ laser energy (caution: 1D)
Margins, eg ITF(1), for SI targets can be measured with 1D simulations(2)

- Run simulations with hot spot reactivity $<\sigma v>_{DT}$ multiplied by a factor $\xi < 1$
- Find values of $\xi$ for $G = 1$, and for high $G$ (eg, 80% of nominal 1D “clean” gain)
- $\text{ITF} = \text{ITF}(\xi)$
- Similarly to Anderson(3), we use $\text{ITF}^* = (\xi G_{\text{crit}})^{-3/2}$

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(3) K. S. Anderson et al., LLE Review 133, 1; Phys. Plasmas 20, 056312 (2013)
Points on the previous gain curves have small ITF* (in all cases ITF* < 1.9)

- Scaled targets have nearly the same ITF*

\[ \text{Gain} \]

\[ \text{Total laser energy, } E_L \text{ (MJ)} \]

\[ \xi_G = 0.71 \text{ (a) } \]
\[ \xi_G = 0.77 \text{ (b) } \]

\[ \xi_{G,\text{crit}} = 0.92 \]
\[ \xi_{G,\text{crit}} = 0.97 \]

\[ \lambda = 0.351 \mu m \text{, scaling b) } \]
\[ \lambda = 0.351 \mu m \text{, scaling a), } S_m = 1.25 \]
\[ \lambda = 0.351 \mu m \text{, scaling a), no spike} \]

\[ \text{Scaled targets have nearly the same ITF*} \]

\[ \Rightarrow \text{We have to define a new reference point (scale } s = 1) \]
Robustness, $\text{ITF}^*= (\xi_G^{\text{crit}})^{-3/2}$, can be increased by either increasing the implosion velocity $u_{\text{imp}}$ or spike power. We choose to increase $u_{\text{imp}}$. 

![Diagram showing the relationship between spike power ($P_s$) and implosion velocity ($u_{\text{imp}}$). The graph demonstrates the critical spike power ($\xi_G^{\text{crit}}$) at different implosion velocities. The previous reference point has a spike power of 0.70 TW at 280 km/s, while the new reference point has a spike power of 0.32 TW at 360 km/s. The region marked as "no gain" indicates a threshold for achieving gain in the experiment.]
Targets with $\text{ITF}^* = 2.8 - 3$, scaled at constant ratio $u_{\text{imp}}/u_{\text{ig}}$:

energy gain $> 100$

at $E_{\text{laser}} < 1 \text{ MJ}$ and implosion velocity below 300 km/s

\[
\frac{\xi_{G}}{\xi_{G}^\text{crit}} = 0.5 \quad (\text{ITF}^* = 2.8)
\]

- $s = 2.76$; $u = 243$; $P_{\text{peak}} = 586$
- $s = 2.1$; $u = 265$; $P_{\text{peak}} = 488$
- $s = 1.53$; $u = 293$; $P_{\text{peak}} = 398$
- $s = 1$; $u = 336 \text{ km/s}$; $P_{\text{peak}} = 305 \text{ TW}$
Increasing safety margin (ITF*) at given implosion velocity: bigger target, larger drive energy (but still feasible on NIF or LMJ)
higher ITF* ==> increased 2D robustness (e.g. increased tolerance to displacement)

\[ \xi_G = 0.7 \]

ITF* = 1.8

scale \( s = 1.53 \)

\( E_{\text{laser-total}} = 750 \text{ kJ} \)

\( U_{\text{implo}} = 252 \text{ km/s} \)

Abs. spike \( P = 160 \text{ TW} \)

24 \( \mu \text{m} \) displacement

Yield = 0.4 MJ

\[ \xi_G = 0.5 \]

ITF* = 2.9

scale \( s = 1.53 \)

\( E_{\text{laser-total}} = 826 \text{ kJ} \)

\( U_{\text{implo}} = 293 \text{ km/s} \)

Abs. spike \( P = 160 \text{ TW} \)

32 \( \mu \text{m} \) displacement

Yield = 87 MJ
Conclusions

• SI promising alternative to conventional central ignition
• Targets can be scaled; tests feasible on present facilities
• Issues: laser-plasma interaction at high intensity, cross-beam-energy transfer, low adiabat direct-drive compression, polar direct drive (for use of NIF/LMJ)
• Encouraging experiments on shock generation, LPI, small scale integrated implosion/shock
• Realistic target design in progress: robustness, margins, scalings
• Explore scaled targets robustness to target fabrication errors and laser facility parameters’ fluctuations
• Significant international cooperation