(Laser driven) Inertial Fusion: The physical basis for current and recently proposed ignition experiments

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Based on a plenary talk given at the EPS conference on Plasma Physics, Sofia, June 29 – July 3, 2009;

**Acknowledgments**

For continuous collaboration:
- A. Schiavi (CNISM and Università di Roma “La Sapienza”)

For specific results presented here:
- M. Olazabal Loumé, X. Ribeyre, G. Schurtz (CELIA)
- J. J Honrubia (UPMadrid), J. Meyer-ter-Vehn (MPQ)
- HiPER WP9 (target modeling) group

For permission to use figures/viewgraphs:
- Lawrence Livermore National Laboratory (through S. Haan):
Summary

• ICF principles
  - essential ingredients
  - key requirements /issues

• Ignition experiments at the NIF (indirect-drive, central ignition)
  - laser, target
  - physics basis
  - design vs issues

• Are there alternatives?
  • drive: direct-drive
  • approach to ignition:
    - fast ignition
    - shock ignition

• Conclusions
Inertial confinement fusion (ICF)

- Fusion reactions
  - from a target containing a few mg of DT fuel
  - compressed to very high density ($\rho > 1000$ times solid density)
  - and heated to very high temperature

- No external confinement $\Rightarrow$ fuel confined by its own inertia
  \[ t = \frac{R}{c_s} \text{ with } c_s \text{ the sound speed and } R \text{ linear dimension of the compressed fuel} \]

$\Rightarrow$ confinement parameter: $nR$ or $\rho R$

- Pulsed process: for energy production
  - burn targets at 1 - 10 Hz
  - (Target gain) $\times$ (driver efficiency) $\geq 10$
    
    $150 \quad 7\%$
The reactor cycle: high target energy multiplication (gain) required to overcome cycle inefficiencies

\[ G \eta_D > 10 \]

Diagram:
- Driver (efficiency \( \eta_d \))
- Target (gain \( G \))
- Thermal cycle (efficiency \( \eta_{th} \))

Equations:
- \( E_d = \eta_d E_{in} \)
- \( E_{fus} = GE_d \)
- \( E_{in} = f\eta_{th}GE_d \)
- \( E_{grid} = (1-f) \eta_{th}GE_d \)
The essential physical ingredients of ICF

(homogeneous sphere of DT, radius $R$, density $\rho$)

• **COMPRESSION:**
  burn fraction $\Phi = \rho R / (\rho R + 7 \text{ g/cm}^2)$
  $\Phi > 20\% \implies \rho R > 2 \text{ g/cm}^2$
  mass $m = (4\pi/3)\rho R^3 = \text{few mg} \implies \rho > 200 \text{ g/cm}^3$

• **HOT SPOT IGNITION**
  do not heat the whole fuel to 5 keV
  heat to 5 – 10 keV the smallest amount of fuel capable of self heating and triggering a burn wave
Hot spot ignition condition:
Lawson-like and $n\tau T$ (or $\rho RT$) criteria

$T_h > 7 \text{ keV}; \quad \rho_h R_h > 0.25 \text{ g/cm}^2$

Diagram showing the hot spot temperature, $T_h$ (keV), and hot spot confinement parameter, $\rho_h R_h$ (g/cm$^2$), with distinct regions for DT, isobaric, DT, isochoric, and D burn. The optimal ignition points are indicated. The figure also includes a graph for $\rho_h R_h T_h > 5 (\rho_h/\rho_c)^{1/2}$ (g keV/cm$^2$) vs. $T_h$ (keV).
the standard approach: central ignition

imploding fuel kinetic energy converted into internal energy
and concentrated in the centre of the fuel

implosion velocity for ignition:

\[ u_{\text{imp}} > 250 - 400 \text{ km/s} \]

depending on the fuel mass:

\[ u_{\text{imp}} \propto m^{-1/8} \]

(see, e.g., S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion, Oxford University Press, 2004.)
Hollow shell target, irradiated by a large number of overlapping beams

$R_a = 1.971 \text{ mm}$  
$R_0 = 1.934 \text{ mm}$  
$R_i = 1.760 \text{ mm}$

Plastic ablator, $\rho_a = 0.94 \text{ g/cm}^3$

DT ice, $\rho_{DT} = 0.224 \text{ g/cm}^3$

DT vapour, $\rho_v = 0.5 \text{ mg/cm}^3$
Irradiation, implosion, compression, ignition & burn
(shell with 1.67 mg of DT fuel, irradiated by 1.6 MJ pulse, see later)

3 mm density (g/cm$^3$)

$10^4$ $10^{-1}$ $10^2$

3 mm temperature (K)

$10^2$ $10^5$ $10^8$

simulated interval = 25 ns

S. Atzeni, 1992
Zoom (in space and time):
final compression, ignition, burn and explosion

Density

Temperature

0.15 mm

0.15 mm

simulated time = 0.5 ns

S. Atzeni, 1992
Implosion concentrates energy in space, multiplies pressure, but

four key issues

1. couple efficiently driver energy to the target, to achieve adequate imposion velocity
2. use efficiently the coupled energy to compress the fuel
3. maintain nearly spherical symmetry (small, central hot spot to be created)
4. limit dangerous effects of Rayleigh-Taylor instabilities (RTI)
1st issue: coupling laser light

- use short laser wavelength (e.g. $\lambda = 0.35 \, \mu m$)
- limit intensity $I$ to $10^{15} \, W/cm^2$

=> use hollow shell target, instead of sphere

Good absorption in the collisional regime, at short wavelength

$$p \propto I^{2/3} \lambda^{-2/3}$$

@ $I = 10^{15} \, W/cm^2$

$\lambda = 0.35 \, \mu m$

Pressure $p = 80 \, Mbar$
2nd issue: **compress efficiently**

do not heat before compressing =>
- no “preheating” by fast particles, hard X-rays
- tune the pulse, to reach high pressure gradually

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**“Pulse shaping”**

Laser power carefully tuned, to launch a sequence of properly timed shocks, that approximate adiabatic compression

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1-D “Flow chart”

we want $\alpha = \frac{p(\rho,T)}{p_{\text{Fermi}}(\rho)}$ as small as possible
3rd issue: symmetry: irradiate as uniformly as possible

long scale shape of compressed fuel depends on driving pressure non uniformity

$$\frac{\Delta R}{R} = \frac{\Delta u_{\text{imp}}}{u_{\text{imp}}} = \frac{\Delta p}{p} \approx \frac{2}{3} \frac{\Delta I}{I}$$

we want hot spot relative deformation $\Delta R_h / R_h << 1$

with $R_h$ typically $1/30$ of the initial radius

$$\Rightarrow \frac{\Delta I}{I} << 1/20; \Rightarrow \text{we request } \frac{\Delta I}{I} < 1\%$$

(the larger the ignition margin, the larger tolerable $\Delta I/I$  
(eg, Atzeni, EPL 1990)
4th issue: **Rayleigh-Taylor instability**

unavoidable in inertial fusion

deceleration-phase instability at the hot spot boundary

(2D simulation)

Atzeni & Schiavi, PPCF 2004
4th issue: limit Rayleigh-Taylor instability (RTI)

RTI unavoidable.

To reduce effects
- limit seeds:
  - target defects,
  - short-scale irradiation non-uniformity
- choose less unstable regime (increase ablation velocity)
- limit implosion velocity (trade-off with ignition energy)
Rayleigh-Taylor instability hinders hot spot formation and ignition (multimode perturbation with rms amplitude at the end of the coasting stage = 1.5 µm)

Ion temperature (eV) map evolution
A too large initial corrugation amplified by RTI, makes hot spot formation impossible

Ion temperature (eV) map evolution

CASE X3M13
TIME = 0.060 ns
In indirect drive, the fuel containing capsule is irradiated by thermal X-rays (200-300 eV), generated and confined in a cavity (a hohlraum).
Why indirect-drive?

Pros:

• long scale irradiation uniformity weakly dependent on beam disposition
• smooth radiation field on short scales
• RTI less violent than in direct drive, due to much higher ablation velocity (linear growth rate $\gamma = (ak)^{1/2} - k u_{abl}$, with $a$: acceleration, $k$: mode number, $u_{abl}$ ablation velocity = areal mass ablation rate/density)

Con: lower coupling efficiency

(laser $\Rightarrow$ X-rays $\Rightarrow$ capsule, with loss to generate the radiating plasma, loss from the hole, loss of X in the hohlraum wall)
Ready to test ignition (NIF, LMJ)

- understanding and ability to control all four above issues demonstrated (expts at NOVA, OMEGA)
- required drive temperature, pressure demonstrated
- simulations predict experiments (when RTI mix is included) [still some uncertainties from laser-plasma interactions, RTI mix]
- diagnostics suitable for nuclear environment, large $\rho R$ developed
- design based not only on extrapolation, but also on interpolation (@low energy: data from lasers; @ large energy: from explosions)
- cryogenic targets developed
National Ignition Facility, NIF  
(LLNL, USA)

- Nd:glass laser, with frequency tripling
- total energy per pulse: $1.8 \text{ MJ (} \lambda = 0.35 \text{ } \mu\text{m})$ [today: 1.1 MJ]
- peak power: 500 TW
- 192 beams, pointing error < 60 $\mu$m
- power (of each bundles of beams) programmable (demonstrated dynamic range 1:90)
- operates better than nominal design  (JASON study of the NIC, La Jolla, 14-16 January 2009)
- built between 1999 and 2009; all beam operational, at 65% of power, since March 2009; full power operation from summer 2010.
NIF main goal:
demonstrating ignition, propagating burn and gain > 10

• indirect drive

• point design [see S. Haan et al., PoP 12, 056316 (2005)]
  
  pulse energy: 1.13 MJ
  
  radiation temperature: 285 eV
  
  implosion velocity: 380 km/s
  
  isentrope parameter $\alpha = 1$
  
  yield: 15 MJ

Next: hohlraum, capsule, pulse:

design vs four main issues discussed above
NIF hohlraum coupling & symmetry

symmetry control:
- beam orientation
- beam pointing
- hohlraum aspect ratio
- hohlraum fill

beam coupling: choice of materials

entropy control: cryogenic fuel

courtesy of LLNL
**NIF capsule & pulse efficiency, entropy control, stability**

Be ablator: efficient absorber

Cu graded doping: to avoid preheat to decrease instability

ultra-smooth surfaces: to minimize RTI seeds


Pulse shaping to:
achieve $p > 100$ Mbar,
keeping entropy low

![Image](image-url)
3D simulation of a NIF ignition experiment
S. Haan et al., *NF* 44, S171 (2004), courtesy of LLNL
3D simulation of a NIF ignition experiment

S. Haan et al., *NF* 44, S171 (2004), courtesy of LLNL

60 g/cm$^3$ surfaces
140 ps before ignition

400 g/cm$^3$ surfaces
at ignition

a) DT-ablator interface
   hot-spot surface

b) stagnation shock
   hot-spot surface

50 µm
The National Ignition Campaign is focused on preparing for the first ignition experiments in 2010.

<table>
<thead>
<tr>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>J F M A M J J</td>
<td>J F M A M J J A S O N D</td>
</tr>
<tr>
<td>NIF Project CD4</td>
<td>Drive temperature $T_{rad}$ demonstration (Scale 0.7)</td>
</tr>
<tr>
<td>96 beams</td>
<td>Symmetry, shock timing, and ablation rate technique demonstration at NIF scale</td>
</tr>
<tr>
<td>192 beams</td>
<td>Optimize drive, symmetry, timing and ablation</td>
</tr>
</tbody>
</table>

Layered targets

Cryo-layered low yield implosions

Re-optimize if needed

low yield implosions

DT Ignition Implosions

DT high yield

courtesy of LLNL
How does energy for ignition scale?  
Any room for ignition at smaller energy?

\[ E_{\text{laser}} = \frac{E_{\text{central ignition}}}{\eta} \]

- \( \eta \): overall coupling efficiency =  
  absorption \* X-conversion \* transfer to capsule \* hydrodynamic efficiency  
  low, to reduce risks associated to asymmetries; can be improved (see, eg L. Suter et al., *PoP* 2000)

- \( M = (\text{large}) \) safety margin > 2  
  to reduce risks due to RTI induced mixing; could be reduced after successful ignition
MJ energy required on NIF to reduce risks

From parametric simulations (Herrmann et al. NF 41, 99 (2001) (*)

- \( E_{\text{central ignition}}^{\text{fuel-1D}} \propto \alpha^{1.8} u_i^{-5.9} p^{-0.8} \)

with \( \alpha = \) isentrope parameter, little room for improvement

\( u_i = \) implosion velocity,

limited to reduce RTI risks;
small increase leads to major reduction of energy

\( p = \) ablation pressure,

limited to reduce laser-plasma instability risks

(*) See also Atzeni & Meyer-ter-Vehn, NF 41, 465 (2001)
The NIF & LMJ original approach
Risk reduction ==> large pulse energy ==> low gain

Significant improvements may be possible, see Suter et al., PoP 7, 2092 (2000)
Ignition at smaller laser energy?
Higher gain?
Simpler targets?

NIF-LMJ designed 15 years ago; since then
- laser progress:
  - smooth beams
  - ultraintense lasers
  - pulse shaping
- new ignition schemes (fast ignition, shock ignition)
- improved understanding of RTI

=>
- New options for direct-drive and/or
- Alternate approaches to ignition
Other schemes have potentials for higher gain.
What’s new for direct drive?

- beam smoothing techniques routinely implemented ==> RTI seeds reduced
- lasers with large number of beams manageable ==> symmetry
- understanding of ablative RTI (theory, simulations, expt.)
  \[ \gamma = (ak)^{1/2} - \beta \, k \, u_{\text{abl}}, \]
  with \( \beta \) dependent on flow and materials ==> choice of ablator materials
  set to high entropy (lower density) the outer part of the shell
  \( \Rightarrow \) higher \( u_{\text{abl}} \) ==> less RTI,
  while keeping very low the entropy of the inner fuel

==> direct drive target designs for both NIF and LMJ
   (eg: McCrory et al.; Canaud et al.)

==> high gain direct drive targets proposed (eg, Bodner et al., PoP 2000)
Adiabat shaping drastically reduces RTI growth

=> great opportunity for direct drive

Atzeni, Schiavi, Bellei 2007, confirmed by Olazabal et al (private commun.) and A. Marocchino et al., to be published

adiabat shaping RX2 technique (Anderson & Betti, 2004)
Alternative routes to ignition: separate compression & heating
Fast ignitor

- Ignition requirements: S. Atzeni, Phys. Plasmas 6, 3316 (1999);
The potentials of fast ignitors

No central hot spot
   ==> relaxed implosion symmetry
       and stability requirements

Lower density (=> lower implosion velocity)
   ==> relaxed stability requirements
   ==> higher energy gain

   because the fuel at ignition is isochoric; we do not
   spend energy to compress the outer fuel to balance
   inner pressure

(see Rosen, 1984; Atzeni 1995, 1999)
At ignition
- central ignition: isobaric fuel
- fast ignition: isochoric (hopefully ...)
- shock ignition: intermediate

Notice the different hot spot parameters (see Atzeni, 1995)
The advantages of fast ignition paid by the need for an ultra-intense (& efficiently coupled) driver

**optimal** parameters for density $\rho = 300$ g/cm$^3$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>delivered</strong> energy</td>
<td>18 kJ</td>
</tr>
<tr>
<td>spot radius</td>
<td>20 $\mu$m</td>
</tr>
<tr>
<td>pulse duration</td>
<td>20 ps</td>
</tr>
<tr>
<td><strong>delivered</strong> pulse power</td>
<td>0.9 PW</td>
</tr>
<tr>
<td><strong>delivered</strong> pulse intensity</td>
<td>7.2 x 10$^{19}$ W/cm$^2$</td>
</tr>
</tbody>
</table>

CPA lasers can meet such requirements

$E \propto \rho^{-1.85}; \quad r \propto \rho^{-0.97}; \quad t \propto \rho^{-0.85}; \quad W \propto \rho^{-1}; \quad I \propto \rho^{0.95}$

Standard fast ignition: how is energy transported to the fuel?
Nonlinear, relativistic plasma physics involved

we have to rely on large extrapolations

Ultraintense laser $\implies$ hot electrons (few MeV) $\implies$ hot-spot creation

$\uparrow$                     $\uparrow$                     $\uparrow$

interaction (at critical density)                     transport (1 GA current)                     deposition (in compressed plasma)

other issue: matching hot electron range energy with hot spot; a lot of current debate
Fast ignition with beam channeling *(hole boring)*

   
   ![Diagram of standard compression](image)
   
   create core with density 600 g/cc.**

2. Channeling Laser Beam.
   
   ![Diagram of channeling](image)
   
   100 psec, $10^{19}$ W/cm$^2$
laser creates channel, pushes critical surface close to core.

3. Ignitor Laser Beam.
   
   ![Diagram of ignitor](image)
   
   5 psec, $10^{20}$ W/cm$^2$
laser generates MeV electrons, sending them into core.

4. Thermonuclear Burn.
   
   ![Diagram of thermonuclear burn](image)
   
   burn spreads rapidly through compressed DT; yield many times input energy.

Cone-guiding: a possible solution to shorten the path from critical surface to compressed fuel


==> experiments programmed at FIREX and OMEGA-EP
HiPER

testing fast ignition at minimum energy

artist's view

70kJ, 10psec, $1\omega$, $2\omega$ or $3\omega$

200-300kJ, 5nsec, $3\omega$
Ignition requirements (density, $\rho R$) and isentrope parameter define minimum compression energy and implosion velocity.

From Betti and Zhou (PoP, 2005), for direct-drive targets:

\[
\rho_{\text{bulk}} \approx 0.6 \rho_{\text{peak}} \approx \frac{500}{\alpha_{\text{if}}} (I_{15})^{0.13} \left( \frac{u_{\text{imp}}}{3 \times 10^7 \text{cm/s}} \right)^{0.96} \text{g/cm}^3
\]

\[
\langle \rho R \rangle_{\text{max}} \approx \frac{1.46}{\alpha_{\text{if}}^{0.55}} \left( \frac{E_{\text{c laser}}}{100 \ \text{kJ}} \eta_a \right)^{0.33} \text{g/cm}^2
\]

we want $<\rho> = 300 \ \text{g/cm}^3$ and $<\rho R > 1 \ \text{g/cm}^2$

$\Rightarrow \alpha_{\text{if}} \leq 1$

compression laser energy $\geq 100 \ \text{kJ}$

$u_{\text{imp}} > 2 \times 10^7 \ \text{cm/s}$
An integrated model produces our (optimistic)
GAIN CURVE:
significant gain at laser energy of 200 -250 kJ
(multiply by 1.5 – 2 to introduce margins)

Notice:
- adiabat shaping to reduce RTI growth
- second harmonic ignition laser or anomalous stopping
- 25% ignition beam coupling efficiency assumed
Baseline capsule

compression laser pulse
- wavelength = 0.35 $\mu$m
- focussing optics f/18
- energy = 130-180 kJ
- absorbed energy = 90-120 kJ

1. Laser driven implosion

- Imploding mass = 0.29 mg
- Implosion velocity = $2.4 \times 10^7$ cm/s
- Hydrodynamic efficiency = 10.5%
- Overall coupling eff. = 7.2%
- In-flight-isentrope (inner surf.) = 1.0
- IFAR at (R=0.75R₀) = 36

(only one of six mesh point drawn here)
2. Assembly with high density \((\rho_{\text{peak}} = 500 \, \text{g/cm}^3)\) and confinement \((\rho R_{\text{peak}} = 1.58 \, \text{g/cm}^2)\) produced central “hole”; density can be increased by high-Z doping dense fuel shell
J. Honrubia, 2007; but many open issues, ....
3. Ignition of compressed fuel assembly

Reference target, irradiated by a beam of particles with range = 1.2 g/cm$^2$, focal spot radius = 20 µm, delivering 20 kJ, in 16 ps.

Fusion yield = 13 MJ.

Ion temperature
Symmetry is still an issue

L. Hallo et al., 2009
t = 11.450 ns; 1 ps after start of ignition pulse

Atzeni & Schiavi, 2009
Inserting a cone?

Light coming from wings of compression beams

Max intensity on cone
~25% of max intensity

CELIA, 2009
electrons with the right temperature needed

\[ E_{ig} (kJ) = 22 \left[ 1 - \exp \left( -1.5/\bar{\varepsilon} \right) \right]^{-1} \]

(Atzeni, Schiavi, Davies, PPCF, 2009)
HiPER baseline target -
e-beam ignition, with e-beam Coulomb scattering

Maps at the end of the optimal beam pulse for ignition

1-D Maxwellian, $<E_e> = 1.5$ MeV
cylindrical beam, source at $z = 70 \, \mu m$
Gaussian pulse, $r_{HM} = 14 \, \mu m$, $t_{FWHM} = 15$ ps
with scattering

beam energy $E_{ig} = 38$ kJ

1-D Maxwellian, $<E_e> = 1.5$ MeV
cylindrical beam, source at $z = 150 \, \mu m$
Gaussian pulse, $r_{HM} = 13 \, \mu m$, $t_{FWHM} = 16.7$ ps
with scattering

beam energy $E_{ig} = 47$ kJ

(SA et al, PoP 2008)
Magnetic fields may help to keep the beam collimated
Conclusion on fast ignition:

Great potential, but a number of issues

- Energy conversion efficiency into igniting beam
- Temperature scaling of fast electrons
- Transport of fast electron beam in hot dense plasma

Anything intermediate between central ignition and fast ignition?

Shock ignition

(Betti et al., 2007; Theobald et al, 2008; Ribeyre et al. 2009)
Shock ignition:

intense laser pulse towards the end of the imposition to generate a strong converging shock

pulse for the HiPER target (Ribeyre et al., PPCF 2009; Atzeni et al, EPS Dublin 2010)
Shock ignition as shock-assisted central ignition(*)

a) strong shock driven by the intense laser spike

plasma corona

non-igniting hot spot

b) bouncing divergent shock

dense fuel

igniting hot spot

(*) thanks to G. Schurtz and X. Ribeyre
A promising alternative
Shock ignition @ HiPER

the shock seems to reduce RTI growth!

Fusion yield (MJ) contours

no shock, no ignition  shock and ignition

a large window for ignition

X. Ribeyre et al., PPCF 2009
Conclusion on shock ignition:

Great potential, deserves serious investigation (@ LNJ, @ NIF?)

- implosion less critical than standard central ignition
- robust & classical (hydro) ignition process
- does not require two different lasers

- principle tested at OMEGA (Theobald et al, 2008)
- can be tested at NIF, LMJ

Issues:
- intense laser interaction and laser-plasma instabilities
- shock interaction with short scale RTI perturbation
Towards the reactor?

A very long path

we have to increase

• driver efficiency x 10
• driver rep rate x 10000
• target gain x 5 – 10

However, potential solutions exists and are being studied
(Diode pumped solid-state lasers)
Conclusions

The physics basis for ignition is understood and “controlled”
Predictive capability

With 40 years of intense research all main issues addressed

Impressive technical progress (laser, target, diagnostics)

Anyhow, the ignition campaign is an experiments,
as such enters a new domain (*terra incognita*)

If ignition is achievement: scientific milestone and boost to IFE

ICF/IFE physics is rich and vital; potential interesting, but little
developed alternative schemes
physicists ready to contribute to next steps