Alternative ignition schemes: ignition conditions, scaling laws, gain curves

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(*) S. Atzeni et al., Nucl. Fusion 54, 054008 (2014)
Summary

• Advanced ignition schemes: what are we looking for?

• Gain curves for advanced ignition schemes: general features

• Overview of ignition requirements for different approaches
  o Fast ignition by electrons
  o Fast ignition by protons/light ions
  o Fast ignition by hydrodynamic flow (impact ignition)
  o Shock ignition

• Gain curves for Shock Ignition, including ignition margins
ADVANCED IGNITION: PRINCIPLES
Advanced ignition schemes:

- **separation** [of compression and ignition]
- **low(er) implosion velocity**

“thermonuclear ignition by a focusing shock wave and the burning of a previously compressed spherical target ...”

As the way of decreasing the driver energy ... separation of the process of compression of the main mass of the fuel and the process of heating of the ignitor is suggested.

[dual-energy heavy ions]
... The purpose of [the] first pulse is to compress ... the main purpose of the second pulse is to bring the central DT region to ignition.

... First a capsule is imploded ... finally the fuel is ignited by suprathermal electrons.

[The fuel is] first imploded by direct laser light with a **low implosion velocity** ... the assembled fuel is ignited from a central hot spot heated by the collision of a spherically convergent ignitor shock and the return shock.
Why fast ignition / alternative ignition schemes

Fast ignition can give more gain and lower threshold energy than indirect or direct drive

Direct drive FI (ρr=3gcm⁻²)

Direct drive FI (ρr=1.5gcm⁻²)

- Higher gain is from lower fuel density in fast ignition
- Lower threshold is from higher ignition hot spot density

Reactor cycle: gain, power to grid, costs

- Close the cycle: \( G \eta_d = 1/(M\eta_{th} f) \)
- Power production: \( P_{grid} = \nu_{driver} E_{grid} = \nu_{driver} [(1-f) \eta_{th} GM E_d] \)
- target cost < 20% COE; (COE: cost of energy)
Reactor likely to require few MJ driver
Cost of target critical

\[ G \eta_d \geq 10 \implies G = 100 \text{ (or larger)} \]

Large capital costs, economy of scale; \( P_{\text{grid}} \geq 1 \text{ GW}_e \implies E_d = 2 - 5 \text{ MJ} \]

cost of target < 20\% Cost Of Energy

\[
\text{cost of target} < \ 28 \ \text{cent} \left( \frac{Y_{\text{fus}}}{250 \text{ MJ}} \right) \left( \frac{COE}{5 \text{ cent/kWh}} \right) \left( \frac{\eta_{\text{th}}}{40\%} \right)
\]
Present and future potential advantages of advanced ignition

IFE regime:
higher gain; smaller driver

ignition demonstration:
much smaller driver
The ICF hot spot ignition condition is essentially a condition on the hot spot pressure

\[ \rho R T = pR \Leftrightarrow n \tau T \]

used in magnetic fusion

\[ \rho_h R_h T_h > 5 \left( \frac{\rho_h}{\rho_c} \right)^{1/2} (g \text{ keV/cm}^2) \]

pressure for ignition:

\[ \rho_h \text{ (Gbar) } > \frac{500}{\left( \frac{R_h}{30 \mu m} \right)} \left( 6 \frac{\rho_h}{\rho_c} \right)^{1/2} \]

S. Atzeni et al. NJP (2013);
J. Lindl et al, NF (2014)
pressure at stagnation is a strong function of the implosion velocity \( (p \sim u_{\text{imp}}^3) \)

**Implosion velocity for standard ignition:**
\[ u_{\text{imp}} > 300 - 400 \text{ km/s} \]

depending of 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:
\[ u_{\text{imp}} = 370 \text{ km/s} \]

**Laser energy for standard ignition depends very strongly on implosion velocity (\(*)\):**
\[
E_{\text{Laser}} \propto \eta^{-1} u_{\text{imp}}^{-6} \alpha_{\text{if}}^{1.8} P_{\text{abl}}^{-0.8}
\]

“low” implosion velocity leads to higher gain than in the standard scheme, if ignition is achieved, at “low cost”, by a separate mechanism

\[
G = \frac{E_{\text{fus}}}{E_L} = \frac{E_{\text{fus}}}{E_{L-c} + E_{L-\text{ig}}}
\]

with

\[
E_{\text{fus}} = m_{\text{i-DT}} \Phi Y_{\text{DT}} \cong 0.125 < \rho R >^{0.8}
\]

\[
E_{L-c} = \frac{1}{\eta_a \eta_h} \frac{1}{2} m_{\text{i-DT}} u_{\text{imp}}^2
\]

\[
G \cong 0.25 Y_{\text{DT}} \eta_a \eta_h < \rho R >^{0.8} \frac{1}{u_{\text{imp}}^2} \frac{1}{1 + \frac{E_{L-\text{ig}}}{E_{L-c}}}
\]

for laser-direct drive [Betti & Zhou, 2005]

\[
\eta_h \propto u_{\text{imp}}^{3/4} (\eta_a I \lambda)^{-1/4}
\]

\[
\langle \rho R \rangle \propto \alpha_{\text{if}}^{-0.55} (E_{L-c} \eta_a)^{0.33}
\]

\[
G \propto \frac{E_{L-c}^{0.27}}{u_{\text{imp}}^{5/4}} \left( \frac{1}{1 + \frac{E_{L-\text{ig}}}{E_{L-c}}} \right) \frac{\eta_a^{1.02}}{\Phi^{0.25} \lambda^{0.7} \alpha_{\text{if}}^{0.55}}
\]
FAST IGNITION
Ignition Schemes in FI

R. Freeman, March 30, 2011
beam parameters for fast ignition
first estimate (scaling $\approx$ OK, front factors small)

we have to create a hot spot with [SA, Jpn. J. Appl. Phys. (1995)]
- $<\rho r>_h = 0.5$ g/cm$^2$
- $T_h = 12$ keV

delivering a pulsed beam
- onto a spot of radius $r_b = <\rho r>_h / \rho$
- in a time $t$ shorter than the hot spot confinement time $r_b / c(T_h)$,

- hence:

$$E_{ig} \propto m_h T_h \propto (<\rho r>_h)^3 T_h / \rho^2 \propto \rho^{-2}$$
$$W_{ig} \propto E_{ig} / t \propto \rho^{-1}$$
$$I_{ig} \propto W / r_b^2 \propto \rho$$

the higher the density, the smaller the energy, but the higher the intensity
(Delivered) beam parameters from a parametric 2-D model study, assuming straight propagation, cyl. beam, constant stopping power

ignition windows (S. A., 1999)

energy - power

\[
E_{\text{ign}} = 18 \left( \frac{\rho}{300 \ \text{g/cm}^3} \right)^{-1.85} \text{kJ}
\]

energy intensity

\[
W_{\text{ign}} = 0.9 \times 10^{15} \left( \frac{\rho}{300 \ \text{g/cm}^3} \right)^{-1} \text{W}
\]

\[
I_{\text{ign}} = 7.2 \times 10^{19} \left( \frac{\rho}{300 \ \text{g/cm}^3} \right)^{0.95} \text{W/cm}^2
\]

• For particle penetration depth \( \leq 1.2 \ \text{g/cm}^2 \); longer range: more energy
Fast ignition requires an ultra-intense (\& efficiently coupled) driver

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

- **delivered** energy: $18 \text{ kJ}$
- spot radius: $20 \mu\text{m}$
- pulse duration: $20 \text{ ps}$
- **delivered** pulse power: $0.9 \text{ PW}$
- **delivered** pulse intensity: $7.2 \times 10^{19} \text{ W/cm}^2$

\[ E \propto \rho^{-1.85}, \quad r \propto \rho^{-0.97}, \quad t \propto \rho^{-0.85}, \quad W \propto \rho^{-1}, \quad I \propto \rho^{0.95} \]
But range and focal spot are not necessarily as desired

\begin{align*}
E_{ig} \text{(kJ)} &= 18 \left( \frac{\rho}{300 \text{ g/cm}^3} \right)^{-1.85} \times \max \left(1, \frac{R}{1.2 \text{ g/cm}^2} \right) \times f(\text{spot radius}) \\
I_{ig} \text{ (W/cm}^2\text{)} &= 7.2 \times 10^{19} \left( \frac{\rho}{300 \text{ g/cm}^3} \right)^{0.95} \times \max \left(1, \frac{R}{1.2 \text{ g/cm}^2} \right) \times g(\text{spot radius})
\end{align*}

Still not included
• Energy spectrum
• Divergence
ELECTRON FAST IGNITION
Hot electron range depends on temperature

Hot electron temperature depends on laser intensity and wavelength

Standard scalings
(with highly questionable front factors); hot-electron spectrum: see later

\[ T_{hot-el} \approx \left( \frac{I^2}{1.2 \times 10^{19}} \right)^{1/2} \text{ MeV} \]

(simplified) ponderomotive scaling; Wilks et al., PRL 1992

\[ R_{hot-el} \approx f_R 0.6 T_{hot-el} \text{ g/cm}^2 \]

\[ f_R = \text{range multiplier} \]

(Tabak, 1994; 2006: \( f_R = 1 \);
Li and Petrasso: \( f_R = 0.8 \);
Atzeni-Schiavi-Davis, 2009: \( f_R = 4/3 \); see later
Betti-Solodov: as ASD)
Accounting for Range $[T_{\text{hot-el}}(I)]$: igniting laser energy < 100 kJ and beam radius reasonable require

either range smaller than classical

or/and short wavelength ignition laser ($\leq 0.5\text{mm}$)

assume 25% ignition laser energy to hot spot (optimistic!)

solid curves: ignition energy at given $f_R \lambda$

dashed: ignition energy assuming no dependence on range, but limitation to beam radius

dot-dashed: no dependence on range; no limitation to beam radius
(Optimistic) GAIN CURVE (*):
significant gain at laser energy of 200 - 250 kJ
(multiply laser $E$ by 2 to introduce margins)

Notice:
- adiabat shaping to reduce RTI growth
- second harmonic ignition laser or anomalous stopping
- 25% ignition beam coupling efficiency assumed (unrealistic, according to more recent simulations)

$\lambda_c = 0.35 \mu m$
$I < 500$ TW/cm$^2$
$\eta_a = 0.7$
$f_{R\lambda_{ig}} = 0.4 \mu m$
$E_{ig}^{laser} < 100$ kJ
$\eta_{ig} = 0.25$

$r_{beam} \geq 20 \mu m$
$\Gamma_{\text{max}} \leq 6$
$\alpha_{if} = 1$

(*) using model by Tabak & Callahan (FED, 2005)
• **3 \(\omega\) laser needed for compression**
  (if \(2\ \omega > 150\ \text{kJ}\) required for the ignition beam)

• **2 \(\omega\) \((\lambda_{ig} = 0.53\ \mu\text{m})\) ignition laser required**
  if 1 \(\omega\) \((\lambda_{ig} = 1.06\ \mu\text{m})\): ignition threshold at 400 kJ

flat adiabat: ignition threshold at 250 kJ
(with 200 kJ for the ignition beam!)
Gain curves similar to the above HiPER curve, obtained by Betti et al., PoP 13, 100703:

Critical issues already apparent from model gain curves by Tabak & Callahan (HIF 2004, Fusion Energy Des. 2005):

see the next two slides
(referring to 1 \( \mu \)m laserlight for ignition)
How do the gain curves depend on the minimum radius of the ignition spot?

No restriction on ignition laser

\[ \lambda_{\text{compr}} = 0.35 \, \mu m \]
\[ \lambda_{\text{ig}} = 1 \, \mu m \]

E_{\text{ign-laser}} < 100 \, kJ

\[ \lambda_c = 0.35 \, \mu m \]
\[ \lambda_{\text{ig}} = 1 \, \mu m \]

spot radius(\( \mu \))
10, 20, 30, 40, 50

Current experiments show e\textsuperscript{-} spreading to 20\( \mu \) spot from much smaller laser spot!
The system gain depends strongly coupling efficiency from laser to ignition region.

No restriction on ignition laser

$\lambda_{\text{compr}} = 0.35 \ \mu m$

$\lambda_{ig} = 1 \ \mu m$

$E_{\text{ign}} < 100kJ$

$\eta_{\text{ign}}$

0.5

0.25

0.12

0.06

$E_{\text{laser}}$ (MJ)
Exponential spectrum vs monoenergetic

uniform sphere
DT plasma, $\rho = 300$ g/cm$^3$

$E_{ig} (kJ) = 22 [1 - \exp(-1.5/\langle\varepsilon\rangle)]^{-1}$

(Atzeni, Schiavi, Davies, PPCF, 2009; similar results with ZUMA-HYDRA: Bellei et al, PoP, 2013)

Still, no beam divergence
velocity distribution, scattering, distance \(d_0\) between e-source and compressed fuel raise the e-beam ignition energy

Optimal \(\langle E \rangle = 1 - 1.5\) MeV

(2D DUED simulations for the HiPER target)

(similar results by Solodov et al., PoP 2007)
Both small-scale experiments and large-scale simulations show large electron beam divergence.
ZUMA (hybrid PIC) – HYDRA (fluid) simulations with PIC computed electron source (spectrum, divergence)

Ignition energy raises to > 500 kJ

C. Bellei et al., PoP 20, 052704 (2013)
ZUMA-HYDRA simulations with PIC computed electron source

**Ignition energy raises to > 500 kJ**

Analogous results from 2D HYDRA simulations of cone-inserted targets [Shay et al. PoP 19, 092706 (2012)]; see also Strozzi et al, PoP 19, 072711 (2012)
Reducing divergence absolutely required:

Applied magnetic fields?
- 50 MG uniform field sufficient [Strozzi et al., PoP 19, 072711 (2012)]
- “magnetic pipes”?

Self generated fields?

[see several talks at this workshop]
ION FAST IGNITION

For specific schemes and recent progress, see

- review by J. Fernandez et al., Nucl. Fusion 2014;
- talk by M. Roth at this workshop
Ion fast ignition: same general requirements on beam energy, power and spot size, laser-hotspot coupling, and for particle range as for the electrons

optimal particle energy:
protons ≈ 8 MeV  
Lithium ions ≈ 120 MeV 
Carbon ions ≈ 500 MeV  
(SA et al., NF 2001)
(Fernandez et al., Honrubia et al., PoP 2009)

if TNSA “wide spectrum”: source must be very close to target => cone-inserted targets

otherwise: monoenergetic ions or in-situ accelerated ions

in-situ, ponderomotively accelerated DT (Naumova et al., PRL; Tikhonchuk et al, NF 2010) or Carbon (Regan et al, PPCF 2011): 100 kJ, \(10^{22}\) W/cm\(^2\), simple target
IMPACT IGNITION
Fast ignition by hydrodynamic flow: Impact ignition

Inelastic collision:
- (part of) projectile kinetic energy $\Rightarrow$ internal energy
- creation of hot spot

Required [as usual(*)]: $(\rho R)_{\text{hot}} \geq 0.4 \text{ g/cm}^2; T > 10 \text{ keV}$

Impactor parameters?
- material
- velocity
- density

Driver energy?

* see, eg., S. Yu Gus’kov and M. Murakami, 2009
Simple previous scheme requires too large velocities and/or too large energy

High-Z impactor [1]:
radiative cooling of impactor (infinite density), hot spot in the fuel;
\( u > 4000 \text{ km/s} \)

(Two-layer) high-Z impactor [2]:
more efficient, still \( u > 2500 \text{ km/s} \)

DT impactor [3,4]:
at impact, same pressure in target and impactor \( \Rightarrow \)
\( \Rightarrow \) Hot spot in the impactor
\( u > 1500 – 2000 \text{ km/s} \);
large impactor density anyhow required [4]:
\( (\xi = \rho_c/\rho_{\text{impactor}}) \)

\[
\frac{T_{\text{target}}}{T_{\text{impactor}}} \approx \frac{\rho_{\text{impactor}}}{\rho_{\text{target}}} = \frac{\rho_{\text{impactor}}}{\rho_c}
\]

\[
E_{\text{impactor}} \approx \frac{56 \text{ MJ}}{(\rho_{\text{impactor}} [\text{g/cm}^3])^2} \left(\frac{(\xi - 1)}{\sqrt{\xi} (\sqrt{\xi} - 1)}\right)^2
\]

Reducing velocity & increasing impactor density

scheme proposed by Gus’kov and Murakami [1]

collision of laser-accelerated multi-layer shell sector with precompressed DT sphere

Ablative acceleration, collision, further compression by pusher

For the three-layer shell:
• \( u \) down to 300–500 km/s
• DT igniter density at ignition \( \equiv 100 \text{ g/cm}^3 \)
• laser energy \( \equiv 800 \text{ kJ} \) [2] \( \Rightarrow \) ignition for total laser energy > 1 MJ

stability a most serious issue: heavy pusher, pusher mass >> DT igniter mass

Impact ignition: demonstration requires MJ laser potential for large gain at multi-MJ level

- Original figure (black curves): M. Murakami et al., Nucl. Fusion 46, 99 (2006);
- Red curve: igniter density accessible with the three-layer scheme
SHOCK IGNITION

concept proposed by Betti et al., PRL 2007
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 pregresses, while shock bounces from center

d) the two shocks collide, and launch new shocks; the imploding shock heats the hot spot
Shock ignition
vs
conventional direct-drive central ignition
A number of targets have been studied(*)
Gain curves computed

(*) by Betti et al.; Ribeyre et al., Schmitt et al.; Canaud et al.; Schmitt et al.; Atzeni et al.; Lafon et al.; Perkins et al., Terry et al., Anderson et al.
HiPER baseline target -- Shock-ignition

**Laser wavelength** = 0.35 μm  
**Compression energy**: 160 - 180 kJ  
**Focal spot**: 0.64 mm (compression)  
0.4 mm (SI)  

**Adiabat-shaping picket**

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**design constraints:**

- Intensity ≤ 5 x 10^{14} \text{W/cm}^2  
  (compression laser; \lambda = 0.35 \text{μm})
- IFAR < 30
- in-flight-<adiabat> ≤ 1.2
- ablation front RTI growth factor  
  \( \max_{l} (\Gamma_{l}) = \max_{l} \left( \int \gamma_{l} dt \right) \leq 6 \)

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Target: S. Atzeni, A. Schiavi and C. Bellei, PoP, 15, 14052702 (2007)  
Pulses: X. Ribeyre et al, PPCF 51, 015013 (2009);  
S. Atzeni, A. Schiavi, A. Marocchino, PPCF 53, 035010 (2011)
Two parameters to be adjusted to achieve ignition: implosion velocity and laser spike power

$\Rightarrow$ design flexibility

for the HiPER target (SA et al, PoP 2007, PPCF 2011)

gain contours in the
(implosion velocity – spike power plane)

15, 045004 (2013)
ignition pressure (=> ignition velocity) decrease with target size scaling to higher energy => flexibility and reduced risks

Spike Intensity (W/cm$^2$)

Implosion velocity (km/s)

a) scaling at fixed implosion velocity
b) scaling at fixed ratio $u_{\text{imp}}/u_{\text{ig}^*}$

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: small margins; see later )

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 \(\text{ITF}^* = (\xi_G^{\text{crit}})^{-3/2}\)

---

Points on the previous gain curves have small ITF* (in all cases ITF* < 1.9)

- Scaled targets have nearly the same ITF*

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

SA et al, EPS 2014; submitted to PPCF
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

$\xi_G^{\text{crit}} = 0.5$ (ITF* = 2.8)

$\begin{align*}
\text{s} = 2.76; \quad u = 243; \quad P\text{peak} = 586 \\
\text{s} = 2.1; \quad u = 265; \quad P\text{peak} = 488 \\
\text{s} = 1.53; \quad u = 293; \quad P\text{peak} = 398 \\
\text{s} = 1; \quad u = 336 \text{ km/s}; \quad P\text{peak} = 305 \text{ TW}
\end{align*}$

SA et al, EPS 2014; submitted to PPCF
Gain decreases as safety margin increases, but still very large at 1 – 2 MJ

SA et al, EPS 2014; submitted to PPCF
Increasing safety margin (ITF*) at given implosion velocity: bigger target, larger drive energy (but still feasible on NIF or LMJ)

SA et al, EPS 2014; submitted to PPCF
higher ITF* ==> increased 2D robustness (e.g. increased tolerance to displacement)

ITF* = 1.8
scale $s = 1.53$

$E_{\text{laser-total}} = 750$ kJ

$U_{\text{implo}} = 252$ km/s

Abs. spike $P = 160$ TW

24 $\mu$m displacement

Yield = 0.4 MJ

ITF* = 2.9
scale $s = 1.53$

$E_{\text{laser-total}} = 826$ kJ

$U_{\text{implo}} = 293$ km/s

Abs. spike $P = 160$ TW

32 $\mu$m displacement

Yield = 87 MJ
Robustness (specifically, tolerance to displacement) can be further increased by increasing spike power.

Also tested, combination of displacement and reduced reactivity (miming mixing)

SA et al, EPS 2014; submitted to PPCF
Great potential, still a few issues for shock ignition

- Laser-plasma interaction at intensities of a few times $10^{15}$ W/cm$^2$
  - generation of ablation pressure about 300 Mbar
  - efficient absorption (low SBS, SRS)
  - not too many and not too hot hot-electrons (*)
- cross-beam-energy-transfer
- Rayleigh-Taylor instabilities (direct-drive, low adiabat)

(*) but moderately hot ($T < 100$ keV) electrons may even strengthen the shock:
R. Betti et al., J. Phys. Conf. Series 112, 022024 (2008);
The end

Thank you for your attention