Overview on shock ignition

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Results from:

- Baton D.
- Batani D.
- Betti R.
- Bell T.
- Canaud B.
- Lafon M.
- Le Bel E.
- Honenberger M.
- Klimo, O.
- Nora R.
- Theobald W.
- Schurtz G.
- Vallet A.
- Tikhonchuk V. T.
Outline

• Shock ignition physics
• Target design optimisation
• 1D gain curve
• 2D simulation results
• Experimental results
Different ways to achieve ignition

**High implosion velocity**

$V_{\text{imp}} \sim 450$ km/s

Central hotspot ignition

1–1.8 MJ, ns, 3ω
550 TW

$G=10$ (Indirect)
$G=30$ (Direct)

Nuckolls (1972)
Lindl (1995-98)

**Low implosion velocity**

$V_{\text{imp}} \sim 150-250$ km/s

Fast ignition:
Electrons, protons, ions

Ignition
100 kJ–1-2ω
7000 TW
15 ps

$G=100$

Tabak (1994)
Kodama (2002)

$V_{\text{imp}} \sim 200-250$ km/s

Shock ignition

Ignition
100 kJ– 2-3ω
200 TW
300-500 ps

$G=100$

Scherbakov (1983); Betti (2005-07)
Ribeyre (2009)
Schmitt (2010)

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Ribeyre (2009)
Schmitt (2010)
Shock ignition or how to ignite low implosion velocity target to achieve high gain

• Low implosion velocity (thicker shell) imply large fuel mass then higher gain for same laser energy

• Thicker shells have good hydrodynamic stability

• Low implosion velocity leads to low hot spot pressure \( (P \sim V_i^3) \)

• Low pressure the hot spot do not ignite \( (P\tau \sim 10 \text{ Gbar ns} : \text{Lawson criteria equivalent to } \rho_h R_h T_h \sim 4 \text{ g keV/cm}^2) \)

• The energy required for hot spot ignition is \( E \sim 1/V_i^6 \sim 1/P^2 \)

How to ignite low implosion velocity target?
Shock ignition principle

Scheme proposed by V. A. Shcherbakov**
and recently by R. Betti et al.*

Shock spike convergence

Shock collisions

Ignition-detonation

Divergent return shock during the shell stagnation phase


Simple means to increase the pressure at target center

1 – Implode at uniform velocity (Noh’s pb (1987) : $ro=64$, $p=64/3$)

2 – Drive a converging shock:
Guderley’s pb (1942)
$ro_{\text{max}}=30$, $P \sim P_0 (r_0/r)^{0.9}$

3 – Drive a converging shock and let it collide with the diverging shock
This is shock ignition

$P=20$

Before collision

After Collision
Choc amplification $x6$

$P=120$
Nora & Betti Shock ignition planar model

Raising the kinetic energy by thickening the shell does not increase the hot-spot pressure

Planar model of a compressible dense slab/shell compressing a low-density gas

\[ V = 3 \times 10^7 \text{ cm/s} \]

\[ \rho \text{ (g/cm}^3) \]

\[ R \text{ (m) } \]

\[ \text{Hot spot} \]

\[ \text{Thick shell} \]

\[ \text{Thin shell} \]

\[ \text{Rigid wall} \]

\[ \text{Hot-spot pressure (Mbar)} \]

Nora R. and Betti R. PoP 18 082710 (2011)
Two different mechanisms related to rarefaction wave propagation limit the hot spot pressure.
Without rarefaction waves, the peak hot spot pressure would be twice as high.
Late shocks can suppress rarefaction waves. There are three ways shocks can be launched.

- **No-rarefaction technique**
  (requires many highly-synchronized “weak” shocks)

- **No-transmission technique**
  (requires one moderate shock)

- **Re-shock technique**
  (requires one strong shock)
The re-shock technique produces the highest hot spot pressure

For shock ignition design, the re-shock technique is used
In Guderley self-similar solution:
the converging shock pressure varies as

\[ P_{\text{shock}}(r) \propto \frac{1}{r^{0.91}} \]

for \( \gamma = 5/3 \)**

Questions:

• How the pressure evolves after the ignitor shock converge and diverge?
• What is the conditions to achieve the ignition of central hot spot?


**Von G. Guderley, Luftfahrt-Forsch. 9, 302 (1942)
Converging-diverging spherical shock wave evolution

Domain of the study
Detonation
Deflagration
Reshocked material
Shell interface

Unshocked material with low temperature
Shock energy material

Converging shock front
Collapse
Diverging shock front
Analytical criterion for hot spot shock ignition (1)

Initial shock velocity

Initial areal density

Analytical criterion for hot spot shock ignition:

\[ d_t E_f > d_t E_r + d_t E_e \]

\[ t = t_c \]

\[ d_t E_f = f_\alpha A_f (t_c) \rho_0^2 u_0^4 r_0^2 \]

\[ d_t E_r = A_r (t_c) \rho_0^2 u_0 r_0^3 \]

\[ d_t E_e = A_e (t_c) u_0^7 r_0 \]

We assume \( \langle \sigma v \rangle \approx \beta T^2 \) \( T \in [8, 25] \) keV

\( f_\alpha : \alpha \) particle energy deposition fraction

Bremsstrahlung emission

Thermal conduction

\*Ribeyre X. et al. PoP 18, 102702 (2011)
Analytical criterion for hot spot shock ignition (2)

Ignition criterion*
\[ d_f E_f > d_r E_r + d_t E_t \]

- **Fusion power**
- **Radiative power**
- **Thermal power**

Initial areal density
\[ \rho_0 r_0 = \sqrt{\frac{A_v u_0^6}{f_\alpha A_f u_0^3 - A_r}} \]

Initial shock velocity

Alpha particle deposited fraction
\[ f_\alpha = f(u_0, \rho_0 r_0) \]

Criterion with total \( \alpha \) deposition

Criterion with \( \alpha \) losses

Shcherbakov criterion**: \[ \rho_0 r_0 u_0^{2.2} \geq K \]

Numerical CHIC Simulations of SI target
- Ignition
- No-ignition

Analytical SI criterion and numerical simulations are in agreement

Extension of the Guderley problem to a finite Mach number (A. Vallet Thesis)

The Mach number is defined by:

$$M_s(t) = \frac{U_s(t)}{c_0}$$

Now vary in time.

The Rannckine-Hugoniot relations are:

\[
\begin{align*}
\rho_1 &= \rho_0 \frac{\frac{\gamma + 1}{\gamma - 1}}{1 + \frac{2}{\gamma - 1}M_s(t)^{-2}}, \\
u_1 &= c_0 \frac{2}{\gamma + 1}M_s(t)(1 - M_s(t)^{-2}), \\
c_1^2 &= c_0^2 \frac{\rho_0}{\rho_1} \left( \frac{2\gamma}{\gamma + 1}M_s(t)^2 - \frac{\gamma - 1}{\gamma + 1} \right).
\end{align*}
\]

There is no self-similar solution, then we search a power series solutions *

Changement of variables and solution

Changement of variable proposed by Sakurai *

\[ x(r, t) = \frac{r}{R_s(t)}, \quad y(t) = \frac{c_0}{U_s(t)}. \]

Hydrodynamic variable Transformation:

\[
\begin{align*}
  u(x, y) &= c_0 \frac{x}{y} \mathcal{U}(x, y), \\
  c(x, y) &= c_0 \frac{x}{y} \mathcal{C}(x, y), \\
  \rho(x, y) &= \rho_0 \mathcal{G}(x, y). 
\end{align*}
\]

Power solution in \( y^2 \) for the scale functions

\[
\begin{align*}
  \mathcal{G}(x, y) &= G(1 + \sum_{k=1}^{\infty} y^{2k} G_k(x)) \\
  \mathcal{U}(x, y) &= U(1 + \sum_{k=1}^{\infty} y^{2k} U_k(x)) \\
  \mathcal{C}(x, y) &= C(1 + \sum_{k=1}^{\infty} y^{2k} C_k(x)) 
\end{align*}
\]

Density profile in Eulerian coordinate

\[ y \rightarrow 0 \quad \text{Gurdeley solution} \]

Solve of N ODE

\[
\begin{pmatrix}
  G_N^r \\
  U_N^r \\
  C_N^r
\end{pmatrix} + \begin{pmatrix}
  A_N \\
  B_N \\
  C_N
\end{pmatrix} + \lambda_N D = F([G_{1..N-1}, U_{1..N-1}, C_{1..N-1}])
\]

* Sakurai, I, J. of Physical society of Japan, Vol. 8, N°5 (1953)
Shock ignition: Stagnation conditions

Two steps process

1. Compression phase
   - Standard quasi-isobaric configuration
     - Low implosion velocity: $V_{imp} < 300$ km/s
     - Hot spot ignition fails
     Identical to fast ignition compression

2. Ignition phase
   With converging shock
   - Non-isobaric configuration
     Increased central pressure and temperature
     Ignites a central hot-spot
Gain of non-isobaric fuel assembly and Rosen model

\[ \varepsilon = \frac{P_h}{P_c} \]

Non-isobaric parameter

\[ G = \frac{\Phi Q_{DT}}{E_L} (M_h + M_f) \propto \varepsilon^{0.27} E_L^{0.17} \left( 1 - \frac{\text{cst}}{E_L} \right) \]

\( \alpha \): Adiabat at stagnation

\( E_L \): Laser energy

Rosen model shows the low threshold and high gain possibility of a non-isobaric configuration

* M.D. Rosen and J.D. Lindl (1984) UCRL-50021-83

Shock igniting of HiPER target

Preliminary results: Robustness study

All DT HiPER target:

1044 µm

833 µm

DT ice

DT gas

Launching window

250 ps confidence interval at 80 TW

180 kJ, 10 ns - 50 TW for compression (3ω)
+ 70-100 kJ, < 500 ps – 150-200 TW for ignitor (3ω)

20 MJ (TN) : Gain ~ 80

The peak laser intensity for ignition thresholds of shock-ignited relevant targets evolves from $1 \times 10^{15}$ to $2 \times 10^{16}$ W/cm$^2$.

- Target design for shock ignition requires implosions that provide safety margins for ignition performance and gain.

- The laser intensity reduces with the implosion velocity of shock-ignited targets:

$$I_L \propto s^{-3/2} \left( \frac{V_I (km/s)}{300} \right)^{-5.6}$$

Raman accelerated hot electrons are probably harmless

PIC simulations indicate that a large fraction of the spike energy is converted into 30 keV hot electrons \(^{(1)}\)

Shell areal mass at spike time is 5-20 times larger than the range of hot electrons \(^{(2)}\)

70 keV
30 keV

\(T_h \approx 250 (\frac{I_{en} \lambda_{lim}}{\rho})^{1/3} \text{ keV} \)

(1) Klimo O. et al. : PPCF 52 055013 (2010)

(2) Betti, R. et al. IFSA 112 022024 (2008)
Hot electrons can generate pressure?

Pressure with spitzer conductivity

Pressure slope change at $5 \times 10^{15} \text{ W/cm}^2$

$P \sim 400 \text{ Mbar}$

Encouraging results but need to be confirmed

(1) Bell T. & Tzoufras. : PPCF 53 045010 (2011)
Rayleigh-Taylor stabilisation by shock during the stagnation \(^{(2,3)}\)

Pressure perturbation only due to low Mode laser illumination \(^{(1)}\)

Compression only

Compression + Shock

RTI was observed In shock ignition OMEGA Experiment \(^{(3)}\)

RTI stabilisation: RMI is reversed by the shock + Ablation par les \(\alpha\)

\(^{(2)}\) Ribeyre et al.: PPCF (2009)

Atzeni results confirmed the mitigation mechanism


\(^{(1)}\) Hallo et al.: PPCF (2009)

\(^{(3)}\) Atzeni et al.: PPCF (2011)
Critical density is half its initial value at spiketime

➤ **use specific RPP and beams for the shock**

Ablation radius \(\sim 1/2\) critical radius

➤ **Efficient thermal smoothing**

➤ **Spike illumination symmetry probably not stringent**

According to 2D simulations, the HiPER target still ignites for non symmetric spikes

Ribeyre et al. : PPCF 51 015013 (2009)
Shock ignition challenges for LMJ

- 1.2 MJ, 390 TW
- 40 quadruplets (33°, 49°)
- Need to have a good laser uniformity < 2%
- May be split and repointed

First step: Target compression at low velocity 250 km/s

Second step: Shock ignition

Need to generate a strong shock 200-300 Mbar
1-5x10^{15} W/cm^2 (3\omega)
A robust target designed for NIF/LMJ class lasers

- Low aspect ratio + Picket: Improves Target Stability
  => peak IFAR ~ 33 IFAR and 0.75R_{inner} = 17
- Al coating: Target protection from IR and prepulse
- CH ablator: Higher Absorption fraction

\[ \langle \alpha_{if} \rangle = 1.2 \]

<table>
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<th>120b PDD Compression + shock spike</th>
<th>Implosion velocity</th>
<th>Performances</th>
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<th>Implosion velocity with shock</th>
<th>Yield t_s~13.4 ns</th>
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<tr>
<td>100 TW +80TW</td>
<td>240 km/s</td>
<td>662 g/cc 2.0 g/cm²</td>
<td>60 TW</td>
<td>265 km/s</td>
<td>44 MJ</td>
<td>94</td>
<td>400 ps</td>
</tr>
</tbody>
</table>
Optimize Polar Drive

- **Repointing Beams**
- **Defocusing Beams**
- **Splitting quads**
- **Tuning Power Balance**: \( w_b \)
  - Intensity on target is linear function of \( w_b \): \( I(\theta, \varphi) = \sum b A_{\theta \varphi b} w_b \)
  - Solve for \( w_b \) \( I(\theta, \varphi) = \bar{I} \Rightarrow (A^\dagger A)w_b = A^\dagger \bar{I} \)

LMJ quad

(we consider only polar repointing)

Defocus and re-pointing possibilities?

- Other possibilities are studied using 49° and 59.5° cones for compression and 33.2° for the shock with new Phase Plate design (Canaud et al. : PPCF 2011)
PDD platform on LMJ (day 1 hardware) : 160 beams Illumination

Compression:
« uniform » Illumination : 1.8%
\[ \langle I_c \rangle = 7.5 \times 10^{14} \text{W/cm}^2 \quad R=R_0 \]

Cones : 33.2° + 49°
Quad splitting + Defocusing (1.8 cm) + Tache focale elliptique

6 cônes
Composite

120 + 40 beams

PDD LMJ

Legendre mode dominant \( l=2-6-10-12-16 \)

Spike
\[ R=0.6 \times R_0 \]
\[ I_{s_{\text{max}}} = 4.8 \times 10^{15} \text{W/cm}^2 \]
\[ \langle I_s \rangle = 3.8 \times 10^{15} \text{W/cm}^2 \]

Bipolar illumination: Uniformity: 10%
2D CHIC simulation of SI LMJ case @ 350 TW

Bipolar Ignition*

- t=14.75 ns, P ~ 4.5 Gbar
- t=14.77 ns, P ~ 5.9 Gbar
- t=14.81 ns, P ~ 12.7 Gbar
- t=14.84 ns, P ~ 100 Gbar
- t=14.9 ns, P ~ 650 Gbar, T_i=10 keV

* In HiPER context see : Ribeyre et al. : PPCF 51 015013 (2009)

IGNITION
Higher neutron yields and areal densities are measured in shock ignition experiments using thick CH targets.

Factor 4 in neutron yield:
- Neutron yields:
  - Compare SI and CHS targets,
  - 40 μm CH shells filled with
  - 25 atm D2 gas

Areal densities:
- Compare SI and CHS targets
- Varying fill pressures

Omega 40+20 beams campaign: shock ignition platform

40 beams:
2.6 % non-uniformity: best symmetry

On critical surface
2 rings:
- 5 beams 37.4°
- 5 beams 79.2°

20 beams:
on Dodecaedron vertices: best symmetry

Drive: 40 beams
Spike: 20 beams

Spike intensities varies by changing the lens defocus

Defocus 3.5 mm
\(<I> \sim 0.5 \times 10^{15} \text{ W/cm}^2\)

Defocus 1.5 mm
I \sim 1 \times 10^{15} \text{ W/cm}^2

Defocus 0.77 mm
I \sim 2.5 \times 10^{15} \text{ W/cm}^2

0.1 \mu m Al
CD

34 \mu m

D_2
401 \mu m

D_2 Pressure
= 25 atm

Incident on target after beam repointing

P (MW)

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5

Intensity on target (10^15 W/cm^2)

0.38

0.39

0.4

0.41

0.42

0.43

Intensity on target (10^14 W/cm^2)

2.5

1.5

0.5

0.25

0.15

0.1

0.05

0.00

Intensity on target (10^13 W/cm^2)
2D CHIC simulations reproduce roughly the measured modulation of the areal density

- 2D CHIC simulation is $\rho R \sim 50 \text{ mg/cm}^2$ Higher (Peak $\rho R$)
- $\rho R$ variation with theta agrees with simulations
Neutron Yield measurement and CHIC simulations

**CHIC 1D**

For all spike intensities, the pressure remain fairly symmetric and constant then the neutron yield too.

The neutron yield is insensitive to spike intensity.

**CHIC 2D**

40 beams only

P=50 Mbar

40+20 beams at spike onset

P=75 Mbar whatever the spike intensity

$I_s \sim 2.5 \times 10^{15} \text{ W/cm}^2$

$I_s \sim 1 \times 10^{15} \text{ W/cm}^2$

$I_s = 0.5 \times 10^{15} \text{ W/cm}^2$
Planar Strong Shock experiment in long plasma corona

![Diagram showing shock waves and laser intensity](image)

LULI: S. Baton et al. (1) (2012)
$I_1 = 7 \times 10^{13} \text{ W/cm}^2$, $I_2 = 10^{15} \text{ W/cm}^2$, $P_s = 40 \text{ Mbar}$, Large 2D effects, Reflectivity < 15% (filamentation?)

PALS: D. Batani et al. (2) (2010-11) (stepped target)
$I_1 = 2 \times 10^{13} \text{ W/cm}^2$, $I_2 = 10^{16} \text{ W/cm}^2$, $P_s \approx 90 \text{ Mbar}$, Large 2D effects, reflectivity < 5% (filamentation?) 30-50 keV hot e

OMEGA: M. Hohenberger et al. (3) (2012)
$I_1 = 2 \times 10^{14} \text{ W/cm}^2$, $I_2 = 1.2 \times 10^{15} \text{ W/cm}^2$, $P_s = 70 \text{ Mbar}$, Low 2D effects, Reflectivity < 7% (SBS+SRS) 1.8% of laser energy in 70 keV hot e

Experimental difficulties to achieve $P_s > 300 \text{ Mbar}$ i.e. intensities larger than $5 \times 10^{15} \text{ W/cm}^2$ (at $3\omega$)

Conclusions

• Important progress has been made in the few last years

But several physical issue need to be resolve to validate shock ignition

• How to High ablation pressure $P > 300$ Mbar ?
  • What is the role of the Parametric instability ?
  • How the hot electron contribute to the pressure ?

• How to keep the hot spot integrity ?
  • What is the role of the shock on the RTI ?

• Converging shock physics study: collision, rebound, amplification, stability, symmetry …

• How to achieve shock ignition on LMJ ?
  • Target design, adiabat shaping, PDD study …

• Need experimental data relevant for shock ignition physics