Laser-Supported Detonation Concept as a Space Thruster

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Raizer pointed out three mechanisms as the propagation modes of laser absorption/heating wave (1966):

- **Breakdown Wave**
- **Detonation Wave**
- **C-J** Propagation Velocity

\[ D = \left[ 2 (\gamma^2 - 1) \frac{I_0}{\rho_0} \right]^{1/3} \]

Radiative mechanism: Form precursor wave
Numerical Study of LSD by Fujiwara Group

- Unsteady Sphere-Symmetry Analyses Using Nonequilibrium Model for Hydrogen
- Unsteady 1-D Analyses for Argon using TVD Scheme
- Unsteady Axi-Symmetric Analyses for Real Geometries
- Unsteady Nonequilibrium 1-D Analyses Including Transport Phenomena
- 1-D Analyses on Steady Mechanism of LSD
Unsteady Sphere-Symmetry Analyses Using Nonequilibrium Model for Hydrogen

Fig. 1 Schematic picture of sphere-symmetry LSD wave

Elementary reactions:
\[ 2H_2 \Leftrightarrow 2H + H_2, \]
\[ H_2 + H \Leftrightarrow 3H, \]
\[ H + e \Leftrightarrow H^+ + 2e. \]

Inverse bremsstrahlung and bremsstrahlung:
\[ H^+ + e + hv \Leftrightarrow H^+ + e, \]
\[ H + e + hv \rightarrow H + e. \]
Unsteady Sphere-Symmetry Analyses Using Nonequilibrium Model for Hydrogen

Radiative Transfer Equations: \[
\frac{d}{dr} \left( I^\pm r^2 \right) = \mp I^\pm \left( K_{ea} + K_{ei} \right) r^2,
\]

Chemically-Reacting Gasdynamic Equations: \[
\frac{\partial U}{\partial t} + \frac{\partial F}{\partial r} = H + S,
\]

\[
U = \begin{pmatrix} 
\rho \\
\rho u \\
e \\
e_e \\
e_h \\
n_e \\
n_a \\
n_m 
\end{pmatrix}, \quad F = \begin{pmatrix} 
\rho u \\
\rho u^2 + p \\
(e + p)u \\
(e_e + p_e)u \\
(e_h + p_h)u \\
n_e u \\
n_a u \\
n_m u 
\end{pmatrix}, \quad H = -\frac{2}{r} \begin{pmatrix} 
\rho u \\
\rho u^2 \\
(e + p)u \\
(e_e + p_e)u \\
(e_h + p_h)u \\
n_e u \\
n_a u \\
n_m u 
\end{pmatrix}, \quad S = \begin{pmatrix} 
0 \\
0 \\
Q \\
Q_e \\
Q_h \\
g_e \\
g_a \\
g_m 
\end{pmatrix},
\]

\[
p_j = n_j k T_j, \quad p = \sum p_j, \quad e_j = n_j \left( f_j k T_j / 2 + \mu_j + m_j u^2 / 2 \right),
\]

Numerical Scheme: MacCormack-FCT Scheme, neutral plasma.
Table 1 Initial Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{e0}$ ($=T_{h0}$) (K)</td>
<td>7000</td>
</tr>
<tr>
<td>$p_0$ (Pa)</td>
<td>5.07x10^5</td>
</tr>
<tr>
<td>$n_{e0}$  ($=n_{a0}$)</td>
<td>1.09x10^21</td>
</tr>
<tr>
<td>$n_{m0}$ (1/m^3)</td>
<td>5.21x10^24</td>
</tr>
<tr>
<td>$n_{m0}$ (1/m^3)</td>
<td>2.96x10^22</td>
</tr>
<tr>
<td>$I_0$ (W/m^2)</td>
<td>1.0x10^12</td>
</tr>
<tr>
<td>$r_{max}$ (m)</td>
<td>2.5x10^-3</td>
</tr>
<tr>
<td>$r_{sph}$ (m)</td>
<td>1.0x10^-4</td>
</tr>
<tr>
<td>Grid Number</td>
<td>1000</td>
</tr>
</tbody>
</table>

Comment: Existence of electron precursor. (b) develop, (c) establish.
Unsteady 1-D Analyses for Argon using TVD Scheme

Fig. 3 Schematic picture of 1-D LSD model

Model:

1-Temperature Model
Transport effect is not considered.

Table 2 Initial Conditions

<table>
<thead>
<tr>
<th></th>
<th>High Temp. Region</th>
<th>Low Temp. Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (atm)</td>
<td>1.00</td>
<td>0.01</td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>10,000</td>
<td>300</td>
</tr>
</tbody>
</table>
Unsteady 1-D Analyses for Argon using TVD Scheme

Fig.4 Development of axial distribution of physical properties by Oshima ($I_0=5\text{GW/ m}^2=0.5\text{MW/ cm}^2$)

Comment: Profiles of $T$, $p$, $u$, $n_e$, $n_a$. (a) Develop, (b) Establish.
Unsteady 1-D Analyses for Argon using TVD Scheme

Comment: 20% lower than C-J velocity ~10 km/sec.
Unsteady Axi-Symmetric Analyses for Real Geometries

![Schematic picture of converging-diverging-nozzle-type LSD model](image)

Fig. 7 Schematic picture of converging-diverging-nozzle-type LSD model

**Model:**

1. **Temperature Model**
   
   Transport effect is not considered.

**Table 3 Initial Conditions**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P (atm)</td>
<td>2</td>
</tr>
<tr>
<td>T (K)</td>
<td>10,000</td>
</tr>
<tr>
<td>I₀ (MW/cm²)</td>
<td>10</td>
</tr>
<tr>
<td>Grid Size (μm)</td>
<td>12.75</td>
</tr>
</tbody>
</table>
Unsteady Axi-Symmetric Analyses for Real Geometries

Fig. 8 x-t diagram of upstream- and downstream-traveling LSDs

Comment: Two LSDs are formed, due to incomplete laser absorption.

Fig. 9 Snapshots of pressure and laser absorption distributions at \( t = 1.257 \text{msec} \)
Unsteady 1-D Analyses
-Nonequilibrium Effect-

Model:

2-Temperature Model

Transport effect is not considered

Table 4 Initial Conditions

<table>
<thead>
<tr>
<th></th>
<th>High Temp. Region</th>
<th>Low Temp. Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (atm)</td>
<td>1.00</td>
<td>0.01</td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>10,000</td>
<td>300</td>
</tr>
<tr>
<td>Grid Size (mm)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Fig. 10 Schematic picture of 1-D LSD model
Unsteady 1-D Analyses
-Nonequilibrium Effect-

Comment: Only LSC is formed; decoupled ionization zone.
Unsteady 1-D Analyses
-Transport Effect-

Model:

2-Temperature Model
Transport effect (thermal conduction, mass diffusion) is considered

Table 5 Initial Conditions

<table>
<thead>
<tr>
<th></th>
<th>High Temp. Region</th>
<th>Low Temp. Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (atm)</td>
<td>1.00</td>
<td>0.01</td>
</tr>
<tr>
<td>T (K)</td>
<td>10,000</td>
<td>300</td>
</tr>
<tr>
<td>Grid Size (mm)</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$I_0$ (MW/cm²)</td>
<td>10.0</td>
<td></td>
</tr>
</tbody>
</table>

Comment: Diffusion contributes to LSD formation.
Unsteady 1-D Analyses
-Transport Effect-

Comment: (a) LSC, (b) LSD.

Fig. 14 Effects of transport phenomena on physical properties (t=2.93μsec).

(a) Without transport effect  (b) With transport effect
1-D Analyses on Steady Mechanism of LSD

Model:
2-Temperature Model
Transport effect (thermal conduction, mass diffusion) is considered

Table 6 Initial Conditions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P(atm)</td>
<td>0.05</td>
</tr>
<tr>
<td>T(K)</td>
<td>300</td>
</tr>
<tr>
<td>Grid Size(mm)</td>
<td>0.005～0.05</td>
</tr>
</tbody>
</table>
1-D Analyses on Steady Mechanism of LSD

Comment: Steady LSD→100% absorption of incident laser.
1-D Analyses on Steady Mechanism of LSD

**Fig. 17** Critical conditions for LSD formation

**Comment:** Critical conditions are clear.

**Theoretical C-J Velocity:**

\[
\frac{D^2}{RT^*} = \frac{(\gamma_0 + 1)^2}{\gamma_0}
\]

*T* : Temperature at sonic point
Conclusions

- Formation of initial absorption zone: Electric discharge.
- Merging between breakdown and shock waves $\rightarrow$ LSD can be formed quickly.
- $1 \sim 10\text{MW/cm}^2$ laser can generate $10\text{km/sec}$ LSD. $I_{\text{sp}} \sim 1000\text{sec}$.
- LSD absorbs 100% of incoming laser.
- C-J condition is satisfied for a steady LSD, when plotted against the sonic point temperature.