Laser-Supported Detonation Concept as a Space Thruster

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Background of LSD Study

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

□Breakdown Wave

□Detonation Wave

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

□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

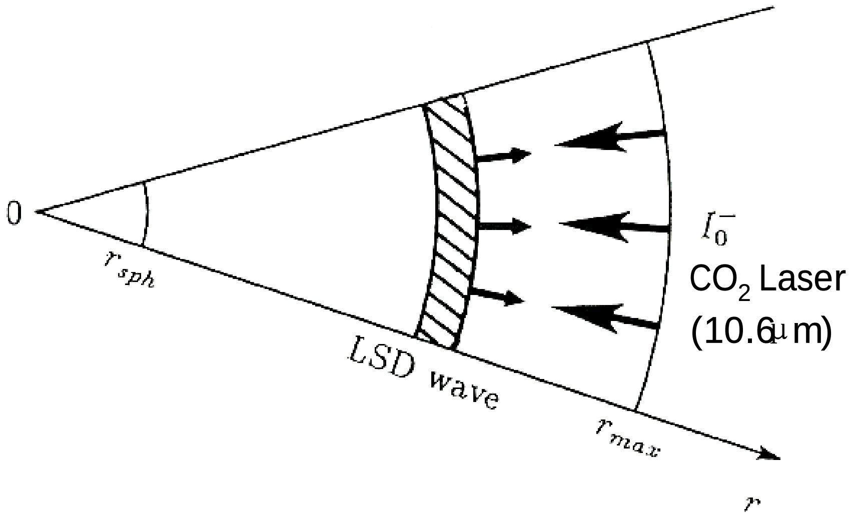


Fig.1 Schematic picture of sphere-symmetry LSD wave

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: $\frac{\partial U}{\partial t} + \frac{\partial F}{\partial r} = H + S,$

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

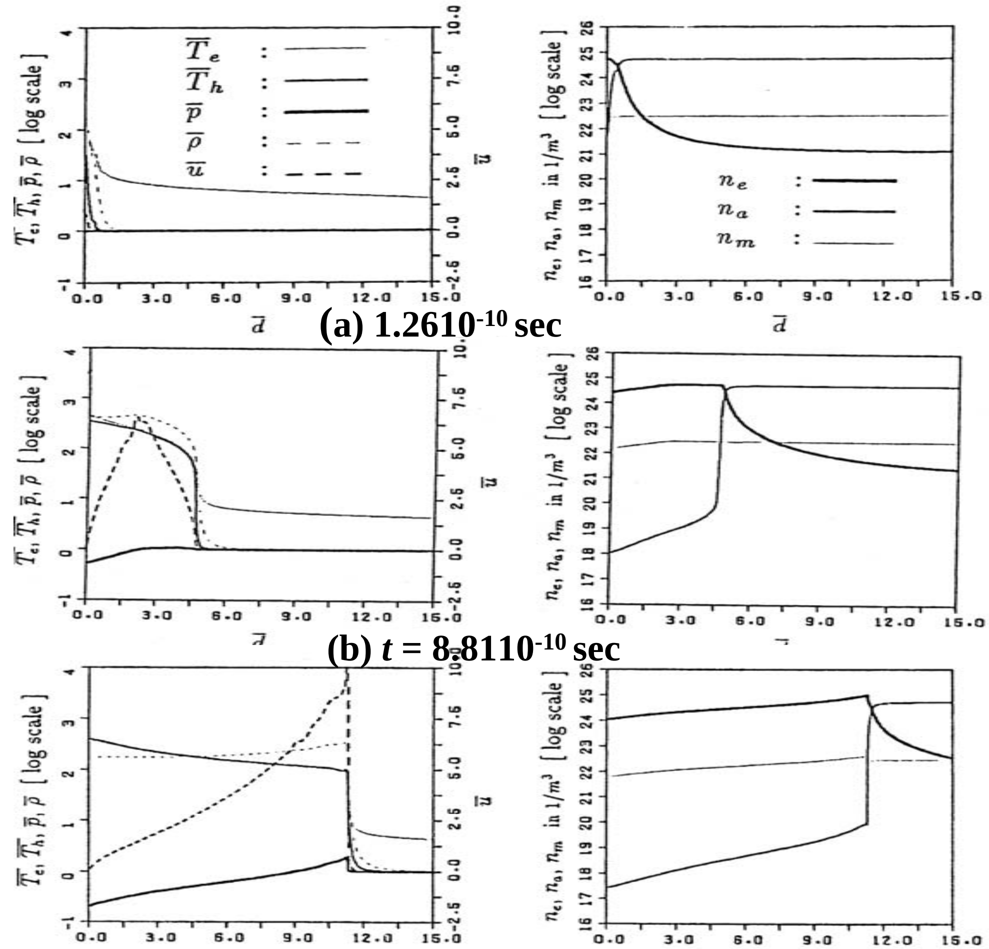
$$p_j = n_i k T_j, \quad p = \sum p_j, \quad e_j = n_j\left(f_j k T_j / 2 + \mu_j + m_j u^2 / 2\right),$$

Numerical Scheme: MacCormack-FCT Scheme, neutral plasma.

Unsteady Sphere-Symmetry Analyses Using Nonequilibrium Model for Hydrogen

Table 1 Initial Conditions

T_{e0} (=T_{h0}) (K)	7000
p_0 (Pa)	5.07×10^5
$n_{\varepsilon0}$(=n_{+0}) (1/m^3)	1.09×10^{21}
n_{a0} (1/m^3)	5.21×10^{24}
n_{m0} (1/m^3)	2.96×10^{22}
I_0^- (W/m^2)	1.0×10^{12}
r_{max} (m)	2.5×10^{-3}
r_{sph} (m)	1.0×10^{-4}
Grid Number	1000



(a) 1.2610^{-10} sec

(b) $t = 8.8110^{-10}$ sec

(c) $t = 3.7410^{-9}$ sec

Fig.2 Development of radial distribution of physical properties by Tsujioka. Subscripts→ e=electron, a=atom, m=molecule, h=heavy particle.

Comment: Existence of electron precursor. (b) develop, (c) establish.

Unsteady 1-D Analyses for Argon using TVD Scheme

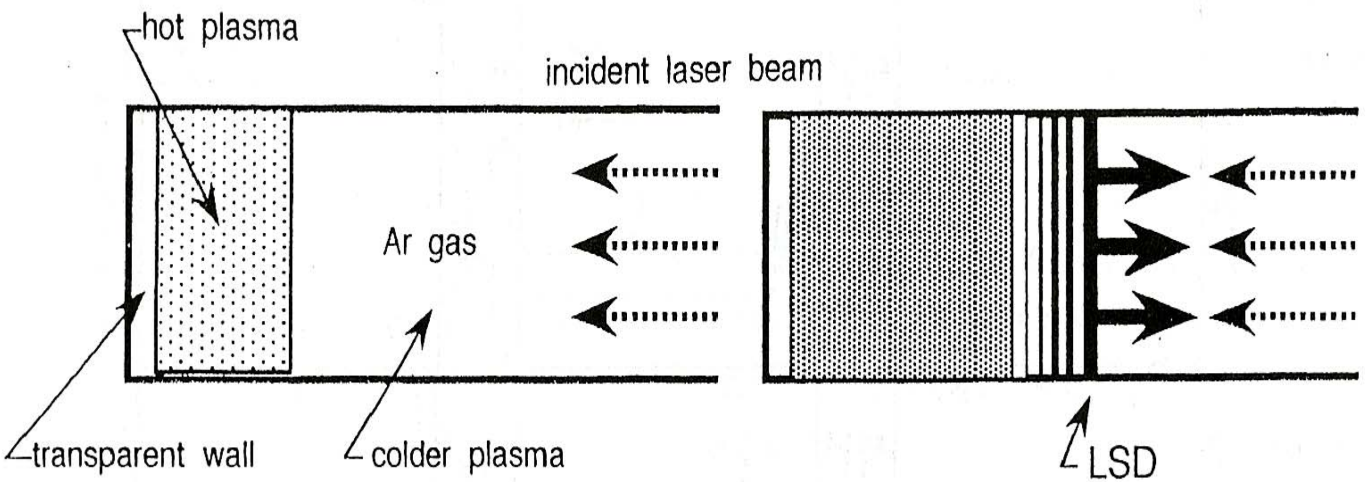


Fig.3 Schematic picture of 1-D LSD model

Model:

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

Table 2 Initial Conditions

	High Temp. Region	Low Temp. Region
P (atm)	1.00	0.01
T (K)	10,000	300

Unsteady 1-D Analyses for Argon using TVD Scheme

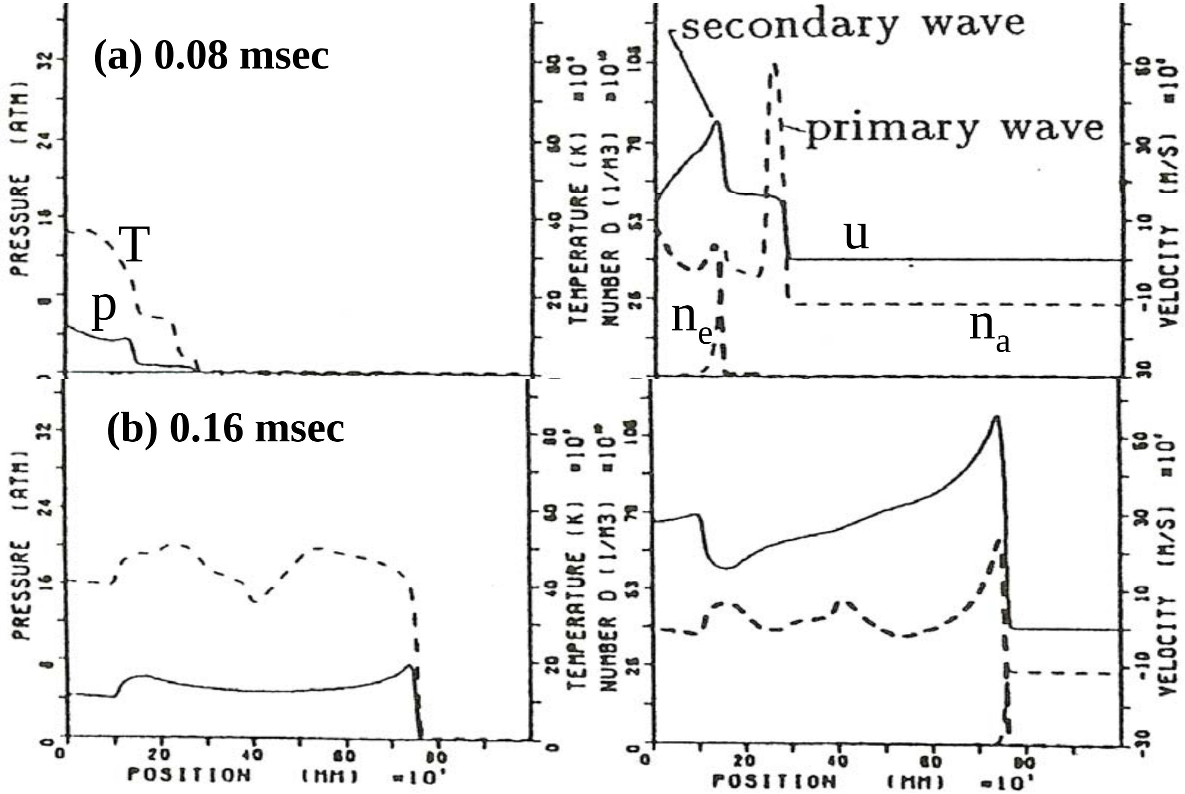


Fig.4 Development of axial distribution of physical properties by Oshima (I_0=5GW/m²=0.5MW/cm²)

Comment: Profiles of T, p, u, n_e, n_a. (a) Develop, (b) Establish.

Unsteady 1-D Analyses for Argon using TVD Scheme

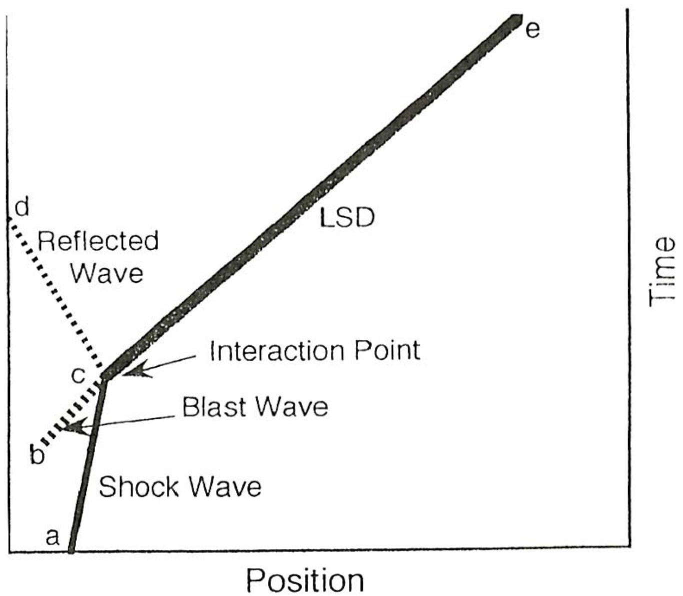


Fig.5 Schematic picture of solution

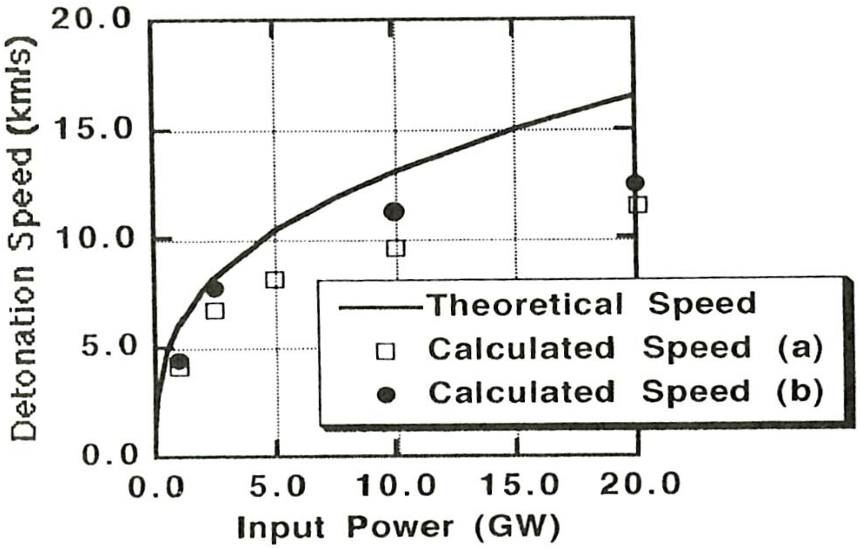


Fig.6 Comparison between calculated and theoretical detonation velocities

Theoretical Velocity by Raizer:

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

Comment: 20% lower than C-J velocity~10km/sec.

Unsteady Axi-Symmetric Analyses for Real Geometries

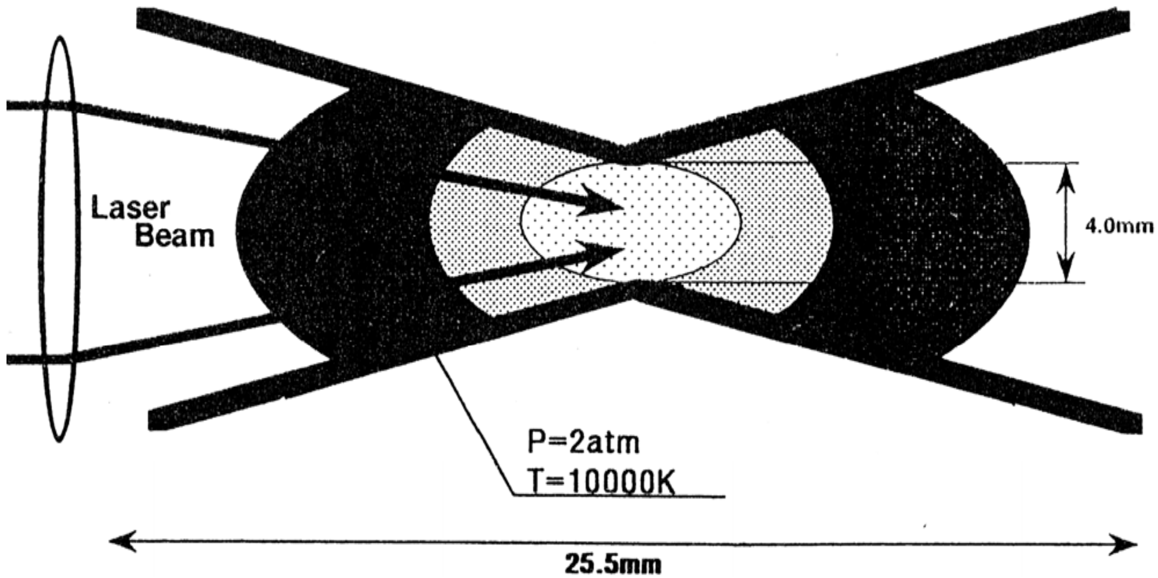


Fig.7 Schematic picture of converging-diverging-nozzle-type LSD model

Model:

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

Table 3 Initial Conditions

P(atm)	2
T(K)	10,000
I_0 (MW/cm^2)	10
Grid Size(μm)	12.75

Unsteady Axi-Symmetric Analyses for Real Geometries

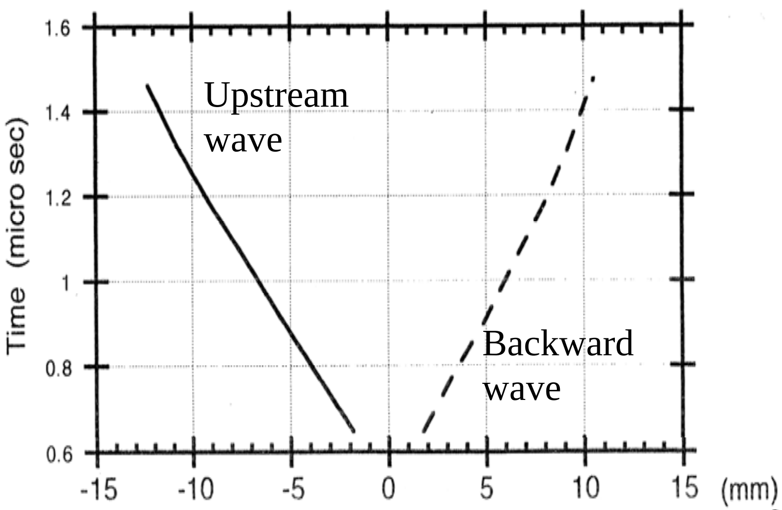


Fig.8 x-t diagram of upstream- and downstream-traveling LSDs

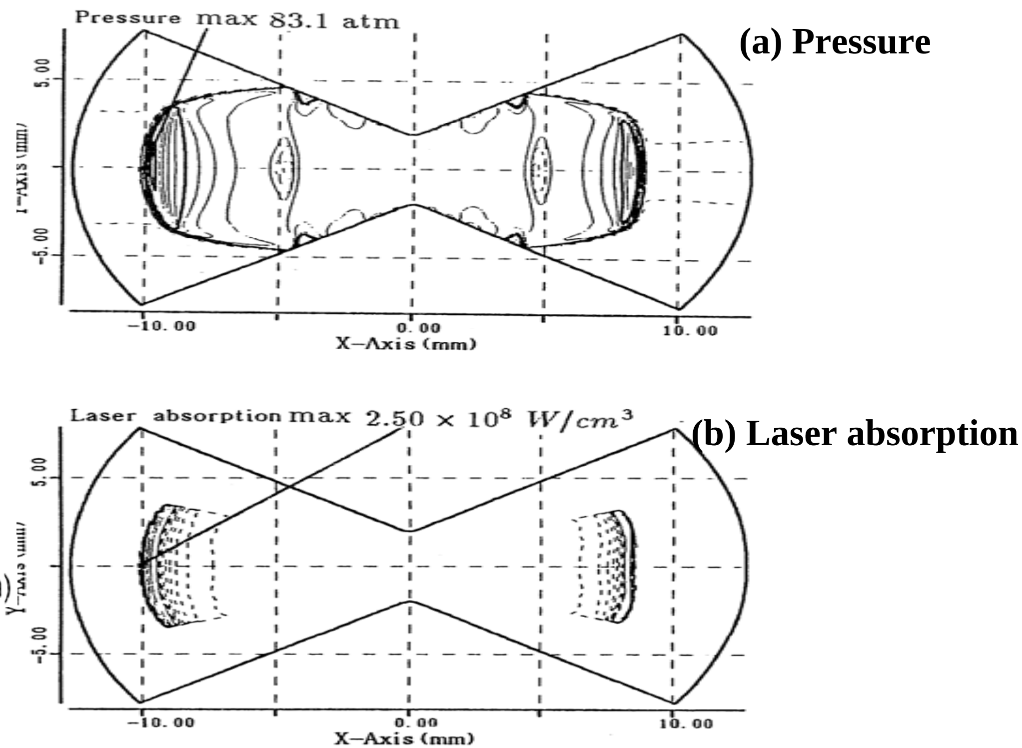


Fig.9 Snapshots of pressure and laser absorption distributions at *t* =1.257msec

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

Unsteady 1-D Analyses -Nonequilibrium Effect-

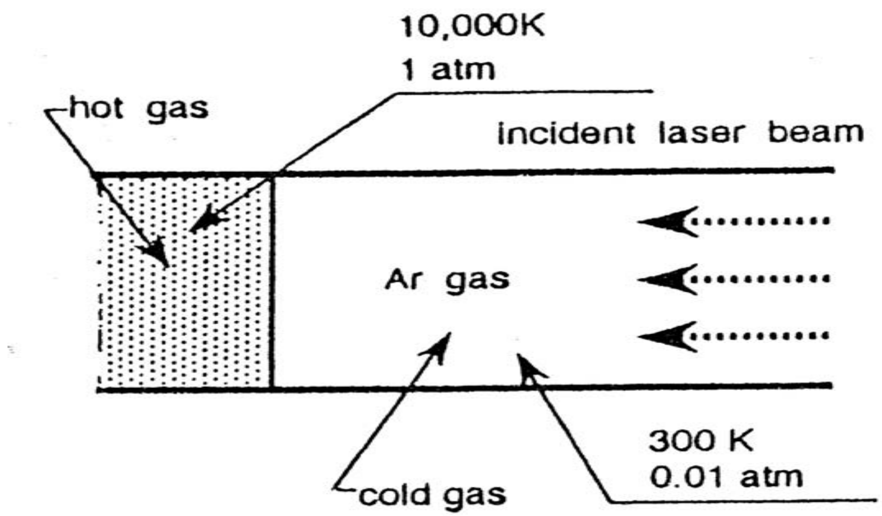


Fig.10 Schematic picture of 1-D LSD model

Model:

- 2-Temperature Model
- Transport effect is not considered

Table 4 Initial Conditions

	High Temp. Region	Low Temp. Region
P (atm)	1.00	0.01
T (K)	10,000	300
Grid Size (mm)	0.01	0.01

Unsteady 1-D Analyses -Nonequilibrium Effect-

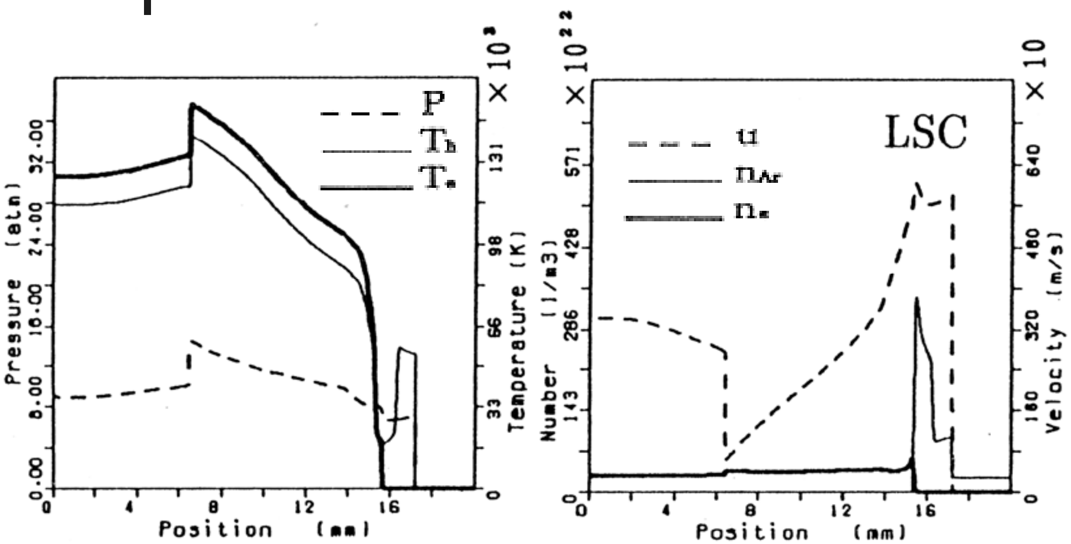


Fig.11 Distribution of physical properties by Shira-ishi (I_0=5.0MW/cm^2)

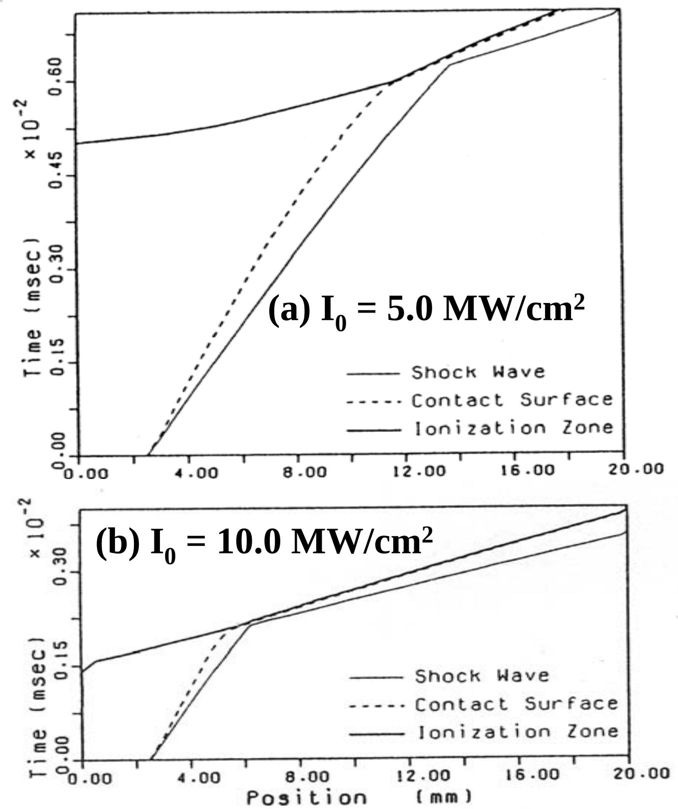


Fig.12 x-t diagram of various waves/fronts

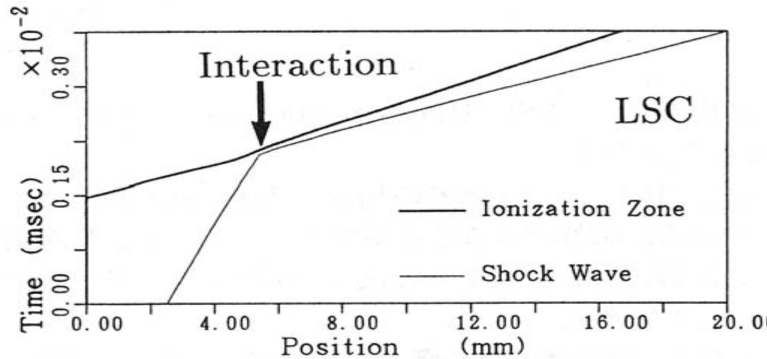
Comment: Only LSC is formed; decoupled ionization zone.

Unsteady 1-D Analyses -Transport Effect-

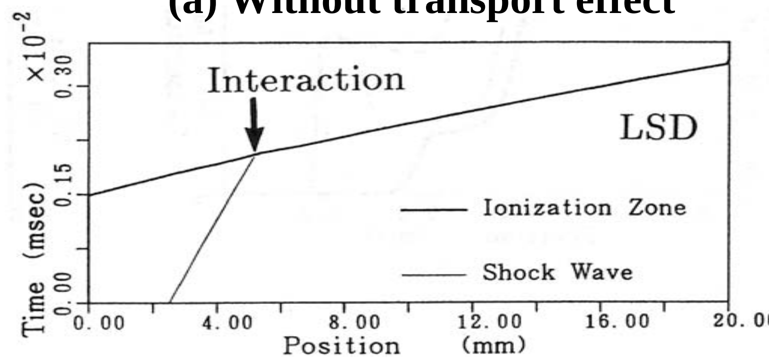
Model:

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

Table 5 Initial Conditions		
	High Temp. Region	Low Temp. Region
P (atm)	1.00	0.01
T (K)	10,000	300
Grid Size (mm)	0.01	0.01
I_0 (MW/cm^2)	10.0	



(a) Without transport effect

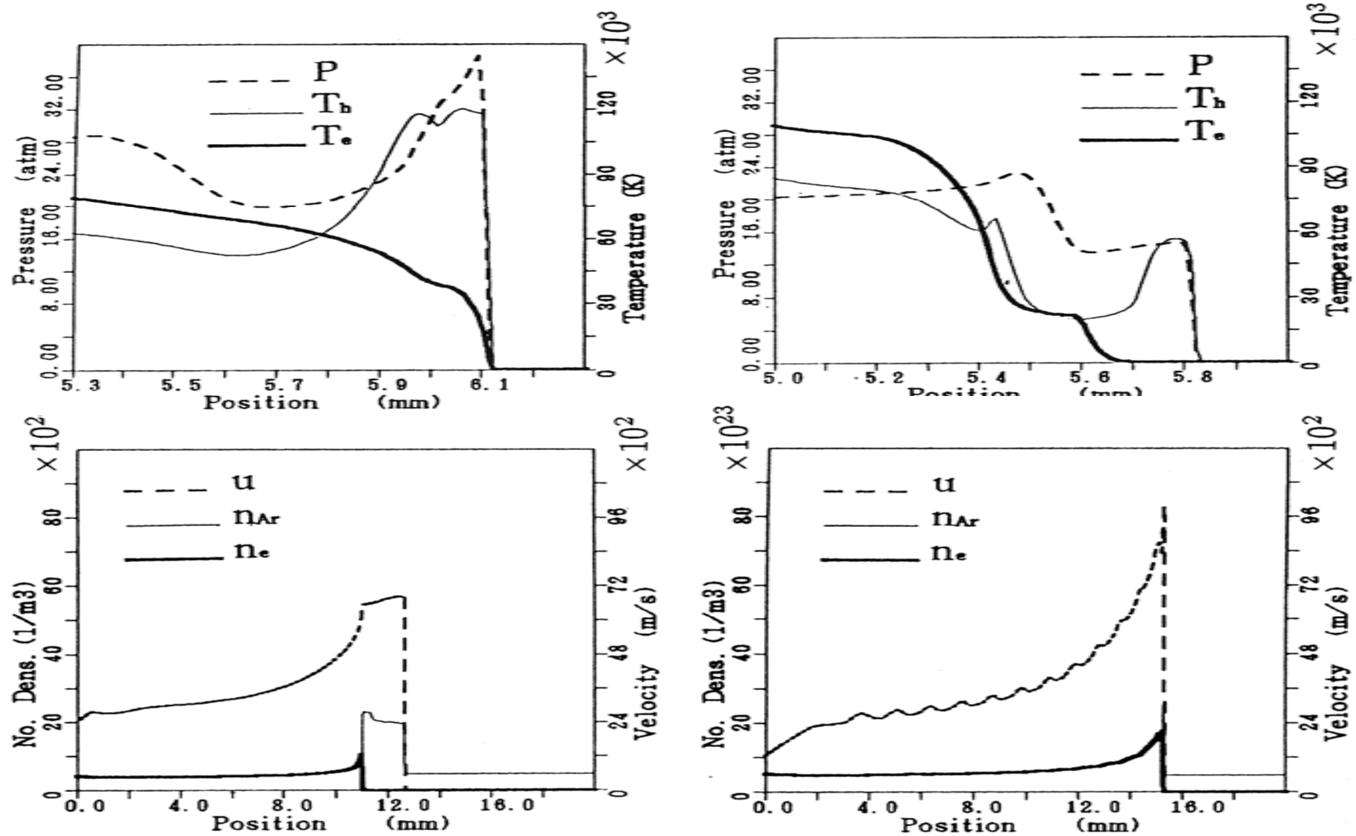


(b) With transport effect

Fig.13 x-t diagram of ionization zone and shock wave.

Comment: Diffusion contributes to LSD formation.

Unsteady 1-D Analyses -Transport Effect-



(a) Without transport effect (b) With transport effect

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

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

1-D Analyses on Steady Mechanism of LSD

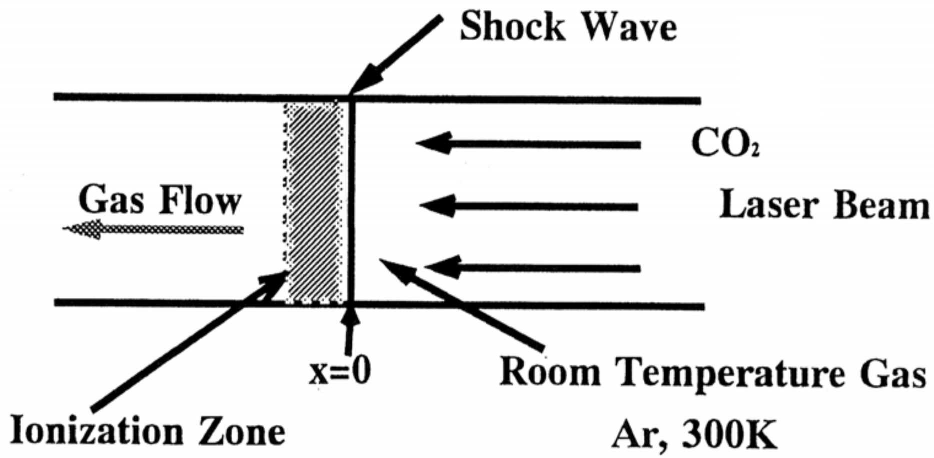


Fig.15 Schematic picture of steady 1-D LSD analysis

Model:

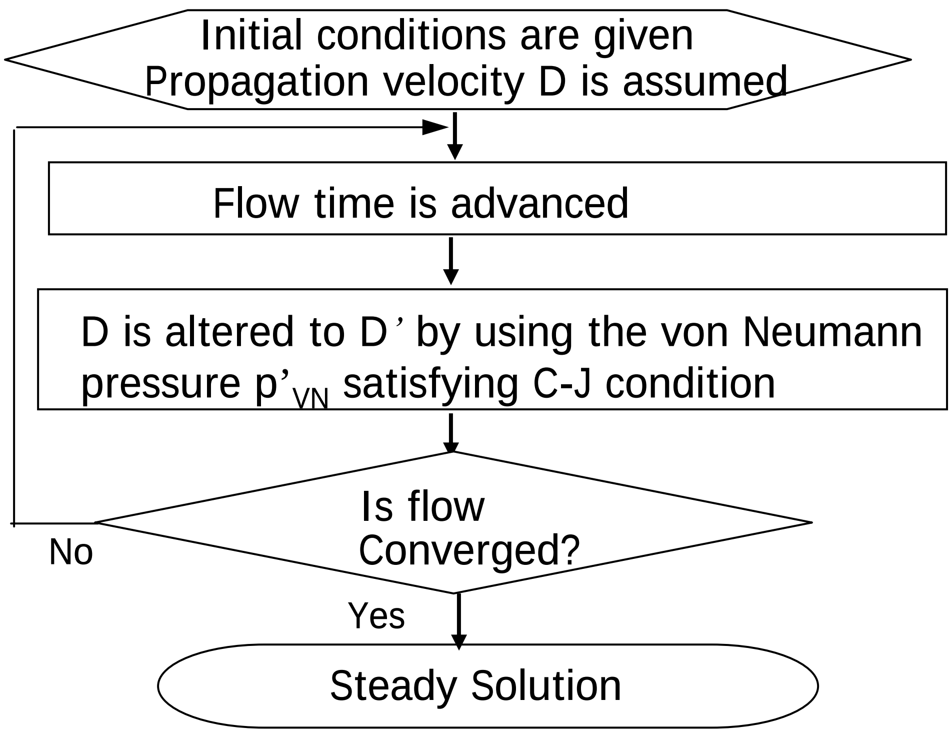
- 2-Temperature Model
- Transport effect(thermal conduction, mass diffusion) is considered

Table 6 Initial Conditions

P(atm)	0.05
T(K)	300
Grid Size(mm)	0.005～0.05

1-D Analyses on Steady Mechanism of LSD

Numerical Procedure



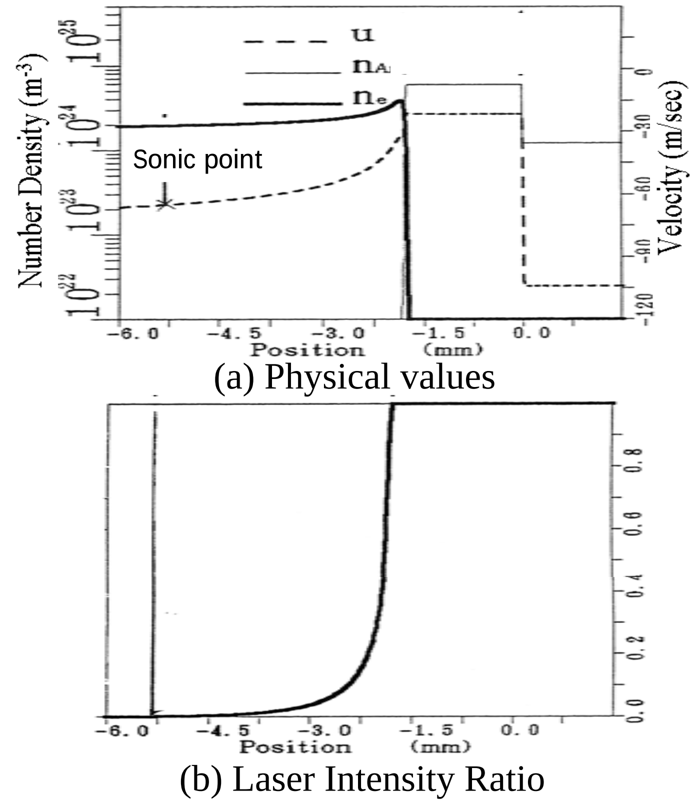


Fig.16 Distribution of physical properties (I_0=5MW/cm^2)

Comment: Steady LSD→100% absorption of incident laser.

1-D Analyses on Steady Mechanism of LSD

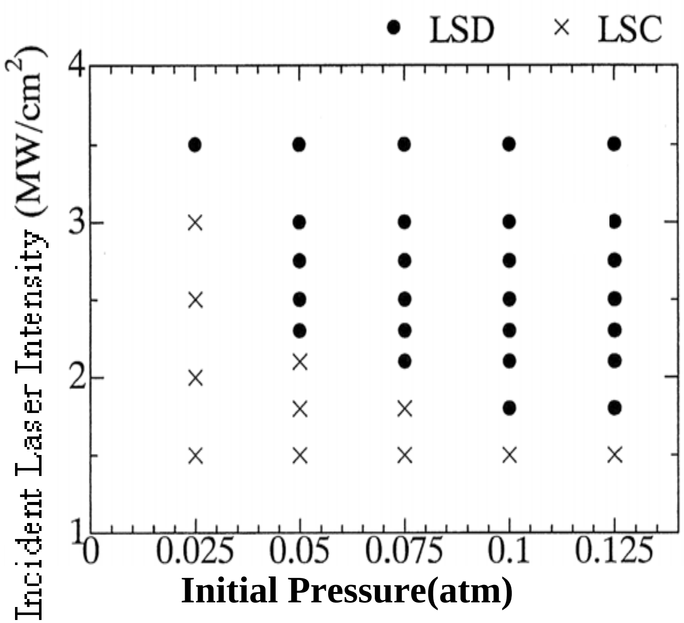


Fig.17 Critical conditions for LSD formation

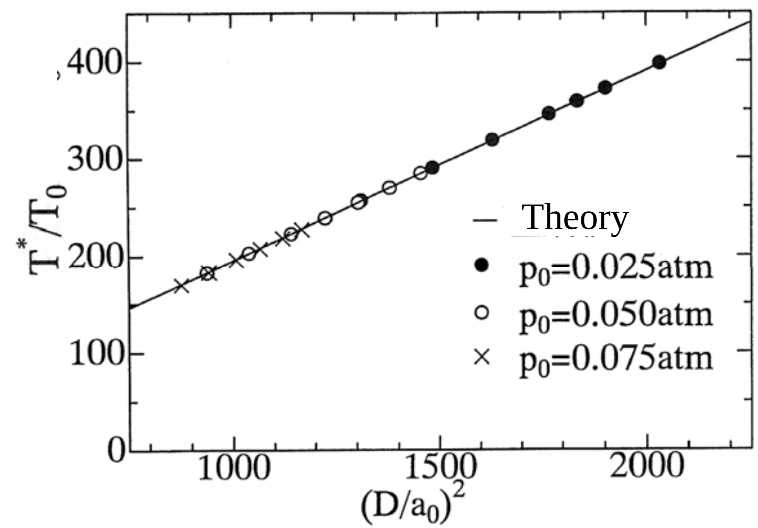


Fig.18 C-J character of steady LSD

Theoretical C-J Velocity:

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

T* : Temperature at sonic point

Comment: Critical conditions are clear.

Conclusions

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