Importance of Capillary Plasma-dynamics for Lasing and Guiding

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• Introduction
• Lasing Condition and Plasma Dynamics
• Laser Guiding Experiments using a Capillary Pinch Plasma
• Simplified analysis on the ionization relaxation and importance of Zeff estimation on the plasma dynamics

• Summary
  – Importance of non-equilibrium ionization effect on the plasma dynamics
  – for Energetic Lasing at Shorter Wavelength and for Formation of Robust Guiding Channel by Capillary Plasma
• Population distribution of pinching-plasma strongly depend on the plasma dynamics
• Structure of core plasma is decided by the interaction of imploding shock wave and the current sheath; i.e., the plasma dynamics

\[ f'(nL) = f(Te, nL, Ti, v_r, dTe/dt) \]

\[ E \rightarrow \text{Gain Coefficient}, \quad V \rightarrow \text{Energy Output} \quad [J] \]

\[ V = \frac{1}{2} R^2 L \rightarrow \text{Effective Lasing Volume} \]
Fast Pulse Power Devices in TITech

High current device

Capillary

High Speed Camera

High rep. device

Reset Circuit

Peak Current 200 kA, dI/dt~10^{12} A/sec

3nF, Max. 900 kV (1.2 kJ)
Lasing Signal

- Lasing Signal
- Rogowski Coil
- Vacuum Pump
- Argon gas
- Pinhole
- Capillary
- Pre-Ionization Unit

Graphs showing:
- Current (kA) vs. Time (ns)
- XRD Signal (V) vs. Time (ns)

Images of XRD patterns at different time intervals:
- (A) 10 - 20 ns
- (B) 20 - 30 ns
- (C) 30 - 40 ns
- (D) 40 - 50 ns

Graph showing Lasing event.
Lasing Signal

Diagram:
- Rogowski Coil
- Capillary
- Pinhole
- Vacuum Pump
- Pre-Ionization Unit

Graphs:
- Current (kA) vs. Time (ns)
- XRD Signal (V) vs. Time (ns)
- XRD Signal (a.u.) vs. Capillary length (mm)

Data:
- GL=12
- g=0.8 cm

Time intervals:
- (A) 10 - 20 ns
- (B) 20 - 30 ns
- (C) 30 - 40 ns
- (D) 40 - 50 ns

Graph (A): 10 - 20 ns, Time: 0 - 50 ns, XRD Signals (a.u.):
- 0, 5, 10, 15, 20, 25, 30, 35, 40
- Current (kA):
  - 0, 10, 20, 30, 40

Graph (B): 20 - 30 ns, Time: 0 - 50 ns, XRD Signals (a.u.):
- 0, 5, 10, 15, 20, 25, 30, 35, 40
- Current (kA):
  - 0, 10, 20, 30, 40

Graph (C): 30 - 40 ns, Time: 0 - 50 ns, XRD Signals (a.u.):
- 0, 5, 10, 15, 20, 25, 30, 35, 40
- Current (kA):
  - 0, 10, 20, 30, 40

Graph (D): 40 - 50 ns, Time: 0 - 50 ns, XRD Signals (a.u.):
- 0, 5, 10, 15, 20, 25, 30, 35, 40
- Current (kA):
  - 0, 10, 20, 30, 40

Graph (E): Current (kA) vs. XRD Signal (V)
- Current (kA):
  - 0, 5, 10, 15, 20, 25, 30, 35, 40
- XRD Signal (V):
  - 0, 5, 10, 15, 20, 25, 30, 35, 40

Graph (F): XRD Signal (a.u.) vs. Capillary length (mm)
- XRD Signal (a.u.):
  - 0, 5, 10, 15, 20, 25, 30, 35, 40
- Capillary length (mm):
  - 10, 20, 30, 40, 50, 60, 70

Graph (G): Log-log plot of XRD Signal (a.u.) vs. Capillary length (mm)
- XRD Signal (a.u.):
  - 10, 100, 1000, 10000
- Capillary length (mm):
  - 10, 20, 30, 40, 50, 60, 70

Graph (H): Scatter plot of XRD Signal (a.u.) vs. Capillary length (mm)
- XRD Signal (a.u.):
  - 10, 100, 1000, 10000
- Capillary length (mm):
  - 10, 20, 30, 40, 50, 60, 70
Lasing Time and XRD Peak Value depend on $P_0$ and $dI/dt$

$d = 3$ mm, $l = 150$ mm, $I(\text{pre}) = 10$ A

Ar: 300 mTorr
Lasing signal depend on initial pressure and dI/dt.
Lasing Time Depend on Discharge Condition

![Graph showing lasing time dependence on discharge condition.]

- Lasing Time (ns)
- \( \frac{dI}{dt} \) (A/ns)

- Ar Gas Pressure (mTorr)
  - 100 mTorr const.
  - 200 mTorr const.
  - 300 mTorr const.
  - 400 mTorr const.
  - 500 mTorr const.
  - 600 mTorr const.
  - 700 mTorr const.
  - 800 mTorr const.

- dI/dt values for different pressure levels:
  - 0-100 A/ns
  - 100-200 A/ns
  - 200-300 A/ns
  - 300-400 A/ns
  - 400-500 A/ns
  - 500-600 A/ns
  - 600-700 A/ns
  - 700-800 A/ns

- Graph legend with different markers for each pressure level.
Initial Pressure: 500 mTorr Ar
Capillary Diameter: 3 mm

Shock wave heating and magnetic compression
- High Temperature
- Internal Structure
MHD Simulation predicts that a robust concave density structure is produced in capillary pinch plasma.

Estimation of opacity effect on gain coefficient indicates the importance of plasma dynamics.

Gain coefficient strongly depend on the velocity gradient of imploding plasma.

\[ n_e = 10^{21} \text{ (cm}^{-3} \text{)} \]
\[ kT_e = kT_i = 860 \text{ eV} \]

\[ n_e = 10^{22} \text{ (cm}^{-3} \text{)} \]
\[ kT_e = kT_i = 860 \text{ eV} \]
Evolution of Ti, Te and Ni in pinching plasma shows that it always far from equilibrium.
Effective Ionization Relaxation Time of Ar Plasma

\( \tau_R \) is relaxation time of argon ions

\[ n_e \times \tau_R \text{ (cm}^3\text{s)} \]

Electron Temperature \( T_e \text{ (eV)} \)

M. Masnavi, M. Nakajima and K. Horioka; to be appear in J. Appl. Phys.
Estimated ionization distribution and $Z_{\text{eff}}$ of Ar on plasma indicate non-equilibrium ionization state.
Effect of Transient Ionization on Ion Abundance and Gain for Heating Plasma

Comparison of Ne-like abundances in steady-state and transient ionization models

\[ \frac{dT_e}{dt} = 20 \text{ eV/ns} \]

Increasing of gain in strongly transient regime for fast plasma heating

Transient Case

Steady-State
Experimental Arrangement for Laser Guiding through Capillary Pinch Plasma

Capillary; 1mmD, 20mmL

2.2TW, 90fs, $10^{17}$W/cm²

4.8kA, 15ns, through pre-ionized He (0.9torr)

Streak photo and MHD simulation predict the concave density structure in the capillary pinch plasma

Streak photograph of capillary discharge
(at pressure of 0.9torr He)

Streak image of transmitted signal of He-Ne probing laser

Bright transmitted light
Streak photo and MHD simulation predict the concave density (guiding) structure in the capillary pinch plasma.

Streak photograph of capillary discharge (at pressure of 0.9torr He)

Current sheet implodes to the axis with a strong shock wave ahead of it, which makes a concave density structure on 8.5nsec from current rise, corresponding to the bright spot image.

Guiding structure

Evolution of the capillary pinch plasma

Imploding plasma makes waveguide structure
Terra-watt laser was guided by the implosion phase of Z-pinch discharge in gas-filled capillary.

CCD images of transmitted Ti-sapphire laser pulse through the 20mm capillary; (a) with discharge plasma and (b) without the plasma.
Evolution of pinching plasma and, naturally, its structure strongly depend on ionization dynamics

Examples of MHD simulation results based on Sesame table and CRE model for Ar filled capillary pinching
Lasing and guiding were demonstrated using capillary pinch discharge

- Lasing strongly depends on the pinch dynamics
- Pinching plasma in capillary almost always far from equilibrium
- Non-equilibrium ionization effect in heating plasma can increase the gain value
- Ionization relaxation should strongly affect the dynamics of capillary pinching plasma; naturally its structure

- For scaling of (Wavelength, power and output energy) VUV Lasers and optimizing the guiding condition in capillary plasmas, analysis on the non-equilibrium ionization process and shock induced structures is of crucial importance