Relaxation Layer in Electro-magnetically Driven Strong Shocks

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Abstract. A study on electro-magnetically driven shock in laboratory experiments is reported. The shock waves are driven by a compact pulse device at 40 km/s into a high-Z gas with 1 µg/cm³. The pulse power device with tapered electrodes can generate a quasi steady and one-dimensional shock. Ion-electron and ionization relaxation processes, based on a steady and 1-Dimensional shock condition, are calculated. Comparison of the experimental result to calculation one indicates that the shocks produced by the pulse power device have potential to observe ion-electron and ionization relaxation layer with an appropriate spatial scale.

1. Introduction
Phenomena accompanied by high Mach number shock waves are of interest because their hydrodynamics is dominated by ion-electron relaxation, ionization process, radiative transfer and also an interplay of them. Their behaviors are connected with many astrophysical phenomena. Experiments of these regime by high power laser have been reported[1, 2, 3]. They contribute to check the astrophysical computer codes and to bridge a gap between laboratory experiments and astronomical phenomena by scaling laws[4].

Experiments for strong shock wave in a wider parameter range should extend their capability. This paper reports the possibility of compact pulse power device as a tool for the strong shock wave physics[5, 6]. The shock wave velocity driven by a pulse power device is about 40 km/s into Xe gas with 1 µg/cm³, which depends on initial upstream pressure. This shock wave can be considered as quasi steady and planar by tapered electrodes and a guiding tube[5]. The shock heated regime satisfies the threshold for significant radiative cooling[3] and also include a relaxation layer, which has appropriate scale length. Therefore, the electro-magnetic pulse device is expected to provide good test samples for study on the structure of strong shock wave with ion-electron relaxation layer and radiative transfer.

2. Experimental Results
The experimental setup of the pulse power device is shown in Fig. 1. To generate a planar strong shock wave, the cross section of the discharge area of the device is gradually decreased with a pair of tapered electrodes and an acrylic guiding tube with constant cross section is located on the top of the tapered electrodes. Twelve plastic capacitors (MAXWELL LABORATORIES, Inc., 0.4 µF 50 kV(max) ) are arranged in a concentric pattern for reducing the inductance.
They are nominally charged to 20 kV and switched by a pressurized gap switch. Change of initial pressure $P_1$ of gas, which is Xe, controls the shock Mach number.

Typical images of plasma evolution at visible wavelength for the high initial pressure, $P_1 = 130$ Pa, and the low initial pressure, $P_1 = 13$ Pa, are shown in Figs. 2(a) and 2(b). From Figs. 2(a) and 2(b), the front average speeds are estimated to be about 10 km/s and 40 km/s, respectively.

As shown, the luminosity pattern between two results is completely different. These indicate that the ion-electron relaxation process and/or radiation transfer affect the shock wave structure.

3. Simulation Results

The obvious difference of images in Fig. 2 motivates the simulation of ion-electron and ionization relaxation layer. The ion-electron equilibration zone is not too small because the density of upstream is about 1 $\mu$g/cm$^3$ which corresponds to $5.0 \times 10^{15}$[cm$^{-3}$] for Xe. In this section, the ionization relaxation simulation is presented under a steady 1-D shock wave condition.

To estimate population distributions, the set of rate equations for ion number density $N(z, i)$ can be written as

$$\frac{dN(z, i)}{dt} = \left[ (I^c(z - 1, i)N_e + I^p(z - 1, i))N(z - 1, i) - (I^c(z, i)N_e + I^p(z, i) + R^{3b}(z, i)N_e + R^f(z, i)N_e)N(z, i) + (R^{3b}(z + 1, i)N_e + R^f(z + 1, i)N_e)N(z + 1, i) \right] (1)$$

where $z$ means the charge state, $i$ means $i$th shell of bound electron, $N_e$ is total electron density, $I^c(z, i)$ is collisional ionization rate coefficient, $R^{3b}(z, i)$ is three body recombination rate coefficient, $R^f(z, i)$ is radiative recombination rate coefficient and $I^p(z, i)$ is photoionization rate coefficient. For simplicity, We assume that ionization state is only ground state in this calculation.

The collisional ionization rate coefficient is obtained as follows[8],

$$I^c(z, i) = 1.24 \times 10^{-6} \xi_{z,i} T_e^{-3/2} \exp(-E_{z,i}/T_e) \left( E_{z,i}/T_e \right)^2 (cm^3/s)$$

where $E_{z,i}$ is the binding energy of the bound electron in the $i$th shell.
where $\xi_{z,i}$ is the number of equivalent bound electrons, $T_e$ is the electron temperature, $E_{z,i}$ is ionization energy. The three body recombination rate coefficient is obtained by the detail balance principle of the collisional ionization rate coefficient as follows,

$$R^{3b}(z, i) = 1.66 \times 10^{-22} T_e^{-3/2} N_e \frac{g_{z,i}}{g_{z+1,i}} \exp(E_{z,i}/T_e) I^c(z, i) \ (cm^3/s) \quad (3)$$

where $g_{z,i}$ and $g_{z+1,i}$ are the degeneracy of a state after/before recombination. The radiative recombination rate coefficient is obtained as follows[9],

$$R^r(z, i) = 5.20 \times 10^{-14} q_{z,i} \left( \frac{E_{z,i}}{T_e} \right)^{3/2} \times \exp(E_{z,i}/T_e) E_1(E_{z,i}/T_e) \ (cm^3/s) \quad (4)$$

where $q_{z,i}$ is effective charge and $E_1$ is exponential integral.

The photoionization cross-section is given as follows[7, 10, 11],

$$\sigma_{bf} = \frac{64 \pi^4 e^{10} m_e q_{z,i}^4}{3 \sqrt{3} h^6 \epsilon_0^3 \nu^7} \ (cm^2) \quad (5)$$

where $e$ is elementary electric charge, $4.8 \times 10^{-10} esu$, $m_e$ is the electron mass, $h$ is the Planck constant, $c$ is light speed, $n$ is principal quantum number and $\nu$ is photon’s frequency in Hz. Therefore, the photoionization rate coefficient is

$$I^p(z, i) = 4\pi \int_{\nu \geq E_{z,i}} \sigma_{bf} \frac{I_\nu}{\hbar \nu} d\nu \ (sec^{-1}) \quad (6)$$

where we assume $I_\nu$ is planckian.

We coupled the rate equations with the following ion-electron energy equations[7, 12],

$$\frac{dT_i}{dt} = -0.0325 n_e \frac{T_i - T_e \Sigma q^2 n_q/(q + 1)}{A T_e^{3/2} \Sigma q n_q} \quad (7)$$

$$\frac{dT_e}{dt} = 0.0325 n_e \frac{T_i - T_e \Sigma q^2 n_q/(q + 1)}{A T_e^{3/2} \Sigma q n_q} - \frac{T_e}{n_e} \left( \frac{dn_e}{dt} \right)_{ion} - \frac{2}{3n_e k_B} \frac{dQ}{dt} \quad (8)$$

where Coulomb logarithm is assumed to be 10.

We can transfer the time evolution of ion population distribution to a spatial evolution with $dz = shockvelocity(40km/s) \times dt$ under the assumption of steady one-dimensional shock waves. We show typical results on the ionization and ion-electron relaxation layer in Figs 3 and 4 with initial electron temperature $T_e^0$ as a parameter. The calculation area starts behind the shock front and $z = 0$ means the shock front. The total ion density is assumed to be $1.4 \times 10^{16}[cm^{-3}]$, corresponding to 4 times of initial Xe gas pressure (13 Pa), and initial ion temperature is assumed to be 430 eV, which is derived by the front speed and classical Rankine-Hugoniot Relation.

4. Discussion and Conclusion
From Figs. 3 and 4, we found that the relaxation length are about 25 mm and 20 mm. The experimental results show that the spatial scale of shock heated region is comparable to these values. We can derive the initial electron temperature, which is initial parameter in this simulation, when future experiments identify ionization states distribution in the shock heated relaxation layer. The electron temperature at just behind the shock should bring us an useful information on the structure of precursor region which is pre-heated by electron
Figure 3. Ion density (a) and ion-electron temperature distributions (b) for $T_e^0 = 3$ eV

Figure 4. Ion density (a) and ion-electron temperature distributions (b) for $T_e^0 = 10$ eV

thermal conduction and/or radiation transport. This means that the electro-magnetic device has potential to quantitatively investigate the structure of strong shock wave with ion-electron relaxation and radiation transfer.

In summary, the results show that our pulse power device not only realizes quasi steady planar shock wave but also enables us to analyze the relaxation layer of strong shock waves.

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