High-Energy-Density Physics Researches based on Pulse Power Technology

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Plasmas driven by pulse power devices are of interest, concerning the researches on high-energy-density (HED) physics. Dense plasmas are produced using pulse power driven exploding discharges in water. Experimental results show that the wire plasma is tamped and stabilized by the surrounding water and it evolves through a strongly coupled plasma state. A shock-wave-heated, high temperature plasma is produced in a compact pulse power device. Experimental results show that strong shock waves can be produced in the device. In particular, at low initial pressure condition, the shock Mach number reaches 250 and this indicates that the shock heated region is dominated by radiation processes.

Key-words; pulse power, high energy density, warm dense matter, shock wave, equation of state, electrical conductivity, radiation transport

1 INTRODUCTION

Properties of dense and/or high temperature plasma are of interests concerning the high energy density (HED) physics. We are working on two topics. The first one is a warm dense plasma made by exploding wire discharges in water and the second is a high temperature plasma induced by a strong shock wave. Both of those plasmas are driven by compact pulse power devices with laboratory scale.

A warm dense (WD) state is produced by a wire explosion in water using a small, cylindrically arranged, pulse power generator. Electrical conductivities are directly estimated from the voltage-current characteristics of the wire explosion. Compared with previous research [1], we intended to make a semi-empirical approach to the exploding wire plasma; we discuss the scaling of equation of state (EOS) and transport coefficients from comparisons of numerical calculations and experimental observations of hydrodynamic behaviors, which cylindrically evolve high density plasma. As the structure and the hydrodynamics of HED plasma are dominated by the EOS and the transport coefficient of them, we can discuss those values from the comparison of experiment observation and numerical simulation. In particular, we propose to use shock wave trajectories in water as a fitting parameter of the hydrodynamic behaviors.

The structure of strong shock waves in high-Z gas is expected to be completely different from that of conventional hydrodynamic shock waves, because relaxation processes and/or radiative processes in the shock heated region affect the structure of shock wave itself [2].

For the discussion of such a complicated hydrodynamics, the geometry should be as simple as possible. The exploding plasma in water is tamped and stabilized by the surrounding water and it makes cylindrically expanding plasma. To make a well-defined, steady state, high temperature plasma, we designed a compact pulse power device, which has a pair of tapered electrodes and a cylindrical guiding tube. This configuration enables us to use one-dimensional assumption.

2 WIRE EXPLOSION IN WATER FOR WARM DENSE MATTER PHYSICS

In order to make warm dense plasmas, thin (50 μ m-100 μ m dia.) wires are exploded in a water-filled chamber. In the experiments, wire materials, their radius and the charge voltage are changed to make the plasma over a wide range of parameters.

2-1 Experimental Arrangement

Figure 1 shows a schematic diagram of the exploding wire discharges in water [3,4]. A capacitor bank C, consists of cylindrically arranged 8x0.4μF low inductance capacitors. The stray inductance Ls of the device was estimated to be Ls=105μH and it drove the wire explosion in water with time scale of μsec. The current and the voltage are measured with a Rogowski coil and a resistive voltage divider. The evolutions of wire/plasma boundary and the shock wave are measured with fast streak/framing camera. From these measurements, we can directly estimate the electrical conductivities of exploding plasma.

2-2 Electrical Conductivity

Using the framing camera, the radius and the particle density was estimated to be typically $10^{21}cm^{-3}$ at 2μsec from start of the discharge. Figure 2 shows the evolution of electrical conductivities of aluminum (Al), copper (Cu), and tungsten (W) wires.

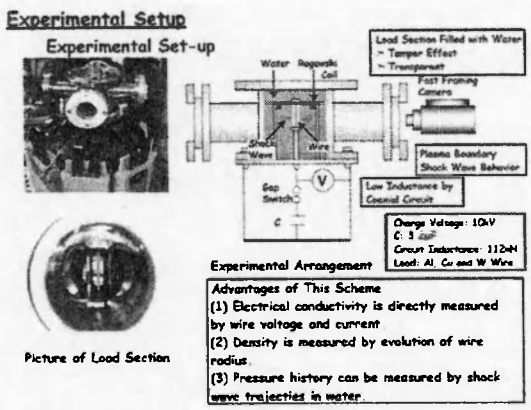

Fig.1 Experimental set-up and photograph of the device for exploding wire experiments

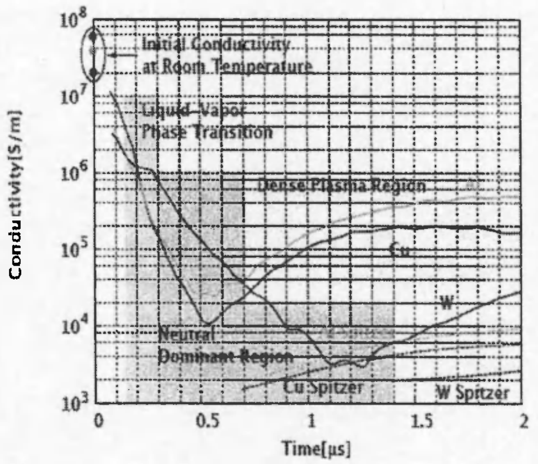

Fig.2 Evolution of conductivities for Al, Cu, and W wire explosion in water

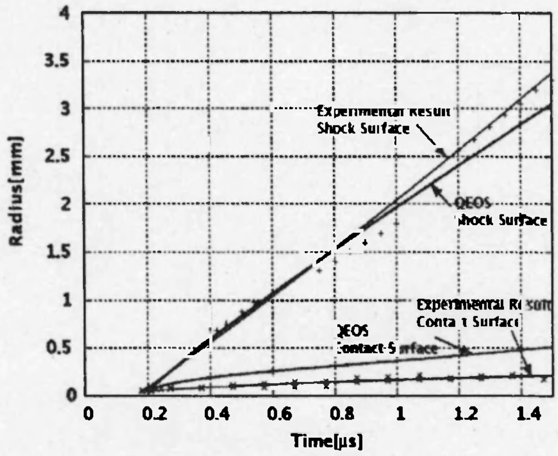

Fig.3 Experimental and numerical evolutions of wire/plasma boundary and shock surface in water

The dotted lines in the figure show theoretical values for conductivities based on a modified Sptzer's model, and as can be seen, the experimental observations of the conductivities are more that 10times of the theoretical values.

We calculate the hydrodynamic behavior of the exploding plasma and the shock wave propagation in water using a 1D magneto-hydrodynamic simulation. To make the calculation, we need EOS models and the transport coefficients. Figure 3 shows the comparison of numerical and experimental evolution of the shock wave and the plasma boundary for Al wire explosion. Experimentally obtained conductivities and Q-EOS model [5] are used in this calculation.

As the hydrodynamics are strongly dependent on the EOS model, we can evaluate its applicability in the parameter region of WD plasma, by using it as a fitting parameter. Especially the numerical shock trace is more strongly affected by that of plasma boundary ;i.e., the EOS model. Figure 4 shows an illustration of the shock trajectory induced by the plasma evolution. The exploding wire/plasma induces a cylindrically developing shock wave, as a piston, through "characteristics" in water. As illustrated in the figure, the shock trace expands the behavior of the plasma motion, both in space and time. This indicates that the shock wave trajectory in water is informative for estimation of the plasma pressure, i.e., for the EOS modeling.

3 FORMATION OF STRONG SHOCK WAVES WITH PULSE POWER DEVICE

Another compact pulse power device is constructed for generation of quasi-steady, one-dimensional, strong shock waves. The cross-section of the discharge region is gradually decreased with a pair of tapered electrodes. The shock wave induced by an electro-magnetically driven current sheet is guided through the tapered section to the top of electrodes. At the end of the electrodes, an acrylic guiding tube is attached to make one dimensional flow [6].

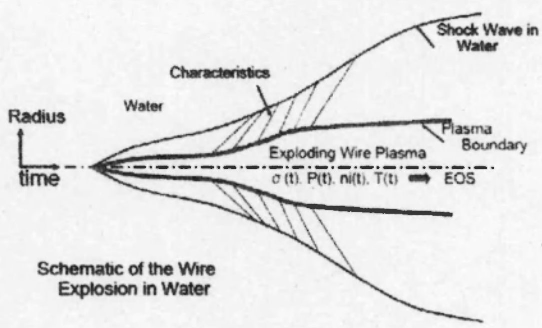

Fig.4 Schematic illustration of exploding wire discharges in water

3-1 Experimental Arrangement

The experimental set up of the pulse power device is shown in Fig.5. The acrylic guiding tube is advantageous to observe the shock wave propagation. The shock speed is measured by a fast framing/streak camera through the acrylic guiding tube. To drive the electro-magnetic pulse, twelve plastic capacitors are arranged in a cylindrical geometry. They are normally charged to 20kV and switched by a pressurized gap switch, which drove 160kA in the discharge chamber.

3-2 Experimental Results

Figure 6 shows typical experimental results. The solid line in the figure shows a criterion of radiative shock based on a steady state one dimensional flow [7]. As shown, the front velocity increased with the decrease of initial filling pressure of Xe. When the discharge chamber is filled with low pressure Xe gas, the shock Mach number M reached M=250, and, as shown in the figure, this value adequately exceeds the criterion for radiative shock waves.

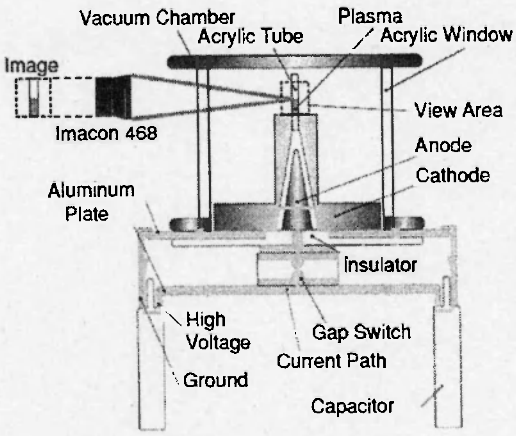

Fig.5 Experimental arrangement for shock heated high temperature hydrodynamics

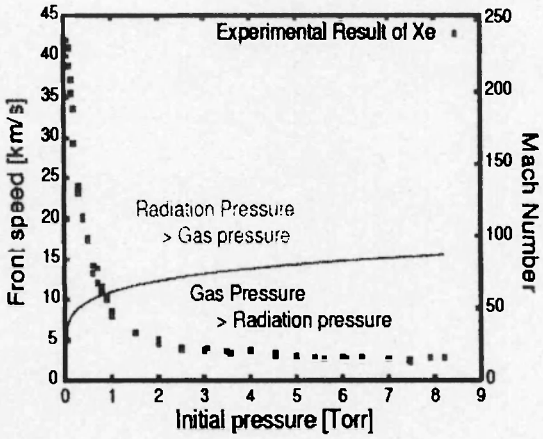

Fig.6 Observed front speed and shock Mach number versus initial filling pressure of Xe

A streak picture is shown in Fig.7, together with a typical numerical calculation of the electromagnetically driven flow of Xe. The upper part is the streak image of the flow and the lower shows a schematic of typical profiles of the relaxation region. In the calculation electron-ion and ionization relaxation process of the Xe plasma is estimated under an assumption of one-dimensional shock heated, steady flow.

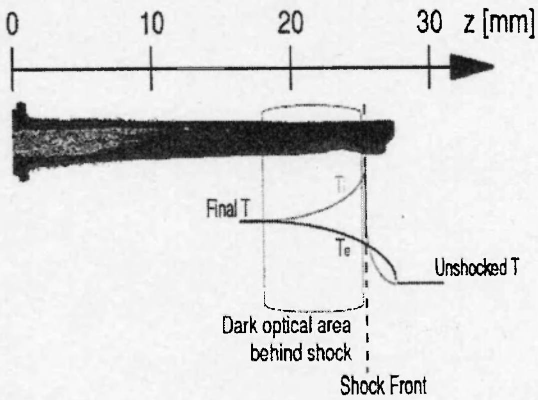

Fig.7 Streak image and typical temperature profiles of shock heated Xe plasma

When the front speed exceeds the criterion derived from the one dimensional simplified analysis, the streak image had an interesting structure [6]. The results indicate that structure of the shock heated region is dominated by the ionization relaxation in Xe plasma and its initial condition should be provided by a radiative process from the heated region. This means from the comparison of experimental observation and numerical calculation, we can quantitatively discuss the effect of radiation transport on the hydrodynamics of heated gas with a strong shock wave.

4 SUMMARY

Plasmas produced by compact pulse power devices are proposed for HED and/or WDM physics. Results show that plasmas made by wire explosion in water can be appropriate sources for scaling of the equation of state and transport coefficients in a wide range of parameters of warm-dense materials. Coupling parameter of the plasma is estimated to be at least 2, up-to discharge time of 2 μ sec. On the other hand, shock wave heated plasmas produced by pulse powered electro-magnetic force in a pair of conical electrodes, are demonstrated to be a suitable one-dimensional test sample for high temperature hydrodynamics involving ionization relaxation and a radiative energy transfer.

These devices can cover a dense moderate temperature region and a high temperature low density region in the density-temperature diagram for HED physics [8]. Advantages of these approaches are compactness, capability of making larger spatial and temporal scale plasmas, and also providing a well-defined condition, compared with those of high power laser methods.

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