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Semi-Empirical Approach to Pulsed Wire Discharges in Water as a Method for Warm Dense Matter Studies

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Hydrodynamic behaviors accompanied by a pulsed thin wire discharge in water have been observed via a fast framing/streak camera, together with the basic electric characteristics. Results show that the discharge plasma is tamped and stabilized by the surrounding water and it evolves through a warm dense state with high degree of symmetry and reproducibility up to a 2 μs discharge time. Numerical simulations show that the shock wave trajectories driven in the water are strongly dependent on equation of state (EOS) models of the plasma. Those results indicate that a semi-empirical fitting of the shock traces to the experimental observation is a useful method for studying the EOS models of matter in a warm dense state.

Keywords:

exploding wire, warm dense matter, strongly coupled plasma, conductivity, equation of state

Properties of dense plasma are of interest concerning the interiors of giant planets, white dwarfs, and the hydrodynamics of fuel pellet of inertial confinement fusion (ICF) [1,2]. Those structures and dynamics are dominanted by the EOS and the transport coefficients of warm dense matter (WDM). A warm dense state is produced using a wire explosion in water by a fast pulse generator. Compared with previous works [3,4], we discuss the hydrodynamic behaviors of the wire explosion over long discharge period, both experimentally and numerically. In particular, we propose to use the shock and contact surface trajectories driven in the surrounding water as reference parameters for scaling EOS and transport coefficients of the WDM, which enables us to evaluate them in a wider parameter regime.

A schematic diagram of the experimental arrangement is shown in Fig. 1. A capacitor bank C, consists of cylindrically arranged 8 × 0.4 μF low inductance capacitors, which drives the wire explosion. The capacitor bank was charged to at least 10 kV to ensure vaporization of the wire. The current and the voltage were measured by a Rogowski coil and a voltage divider. The stray inductance was estimated to be $L = 105$ nH. The evolutions of the wire/plasma boundary and the shock surface were measured by a fast streak camera.

Figure 2 shows a comparison of plasma evolutions driven by wire discharges in air and in water. The results show a beneficial effect of water for making a dense and uniform plasma column: the surrounding water is effective for insulating, tamping, and stabilizing the plasma.

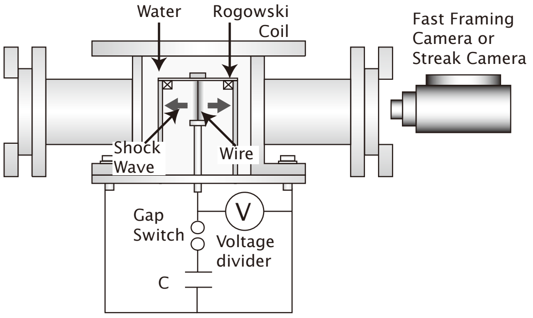

Fig. 1 Schematic setup of pulse-powered wire discharges in water.

Figure 3 shows the evolution of the input energy and resistance of an alminium wire ($r_0 = 50$ μm, 18 mm in length) explosion. The diameter of the wire/plasma is almost constant both in air and in water, while it is in solid - liquid phases. Therefore, the resistance curves overlap until the liquid-vapor phase transition. The resistance curves seen in Fig. 3 indicate the liquid-vapor phase transition occurs at about 200 ns. The required energy for evaporation of the wire is estimated to be 5.1 J. A comparison of the resistance and energy deposition curves also indicates the liquid-vapor phase transition at about 200 ns. After that, the energy input to wire is ceased until 500 ns, due to the increase of resistivity. Using the framing images, the particle density $n(t)$ was estimated from the radius of the wire/plasma column using $n(t) = n_0 r_p^2(t)/r_0^2$ to be about 10^{21} cm^{-3} at 2 μs. Here, subscript 0 denotes the initial value, and $r_p(t)$ is the radius of the plasma boundary. A simple

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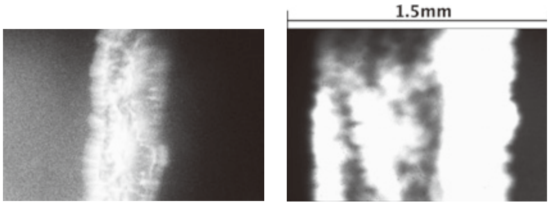
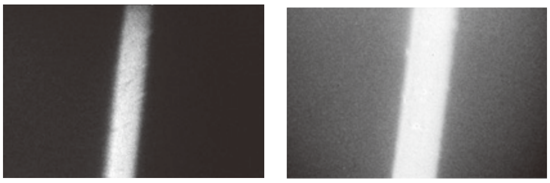


(a) at 240 ns (b) at 300 ns



(c) at 240 ns (d) at 270 ns

Fig. 2 Framing photographs of Al-wire/plasma boundary; (a), (b) in air and (c), (d) in water, with 10 ns gate time.

analytical model indicates that, in the case of the Al-wire explosion, the wire plasma reaches $\rho \sim 0.1$ g/cm^{-3}, $T \sim 10$ eV, the coupling parameter $\Gamma \sim 2$–3, and that the experimentally obtained electrical conductivity was almost 10 times higher than the one using Spitzer's model at 2 μs from the start of the discharge.

We calculate the behaviors of exploding plasma and the shock wave propagation in water using a 1D Magneto-Hydrodynamic (MHD) simulation. To determine the hydrodynamics, quotidian equation of state (QEOS) [5] and the experimentally obtained conductivity histories were used. Figure 4 shows a comparison of the shock wave and the plasma boundary (contact surface) obtained by the experimental and the numerical methods. As shown in the figure, the hydrodynamic behavior, especially the shock wave trajectory, is affected considerably by the EOS models. Note that the contact surface is driven by the pressure gradient at the plasma boundary and the shock trajectory is determined by the propagation of 'characteristics' in water [6] that need a transit time of the order of 10^{-7} sec from the contact surface to the shock front. Accordingly, the shock wave trajectory is determined by the contact surface motion some 10^{-7} sec before the arrival of 'characteristics', and it reflects the pressure history (i.e., EOS) of the wire plasma in a wider spatial and temporal region.

In this paper, we propose, as a method for WDM studies [7], a semi-empirical fitting of the plasma boundary and shock wave evolution accompanied by exploding wire discharges in water. We are planning to evaluate the pressure history of wire plasma based on the shock wave traces and to estimate the plasma temperature using a time-resolved spectroscopy, as a function of input energy rate [8]. These measurements together with the MHD simulation that parametrically include EOS models and/or transport coefficients, should enable us to make the semi-empirical scaling of EOS and electrical conductivity in an extended parameter regime.

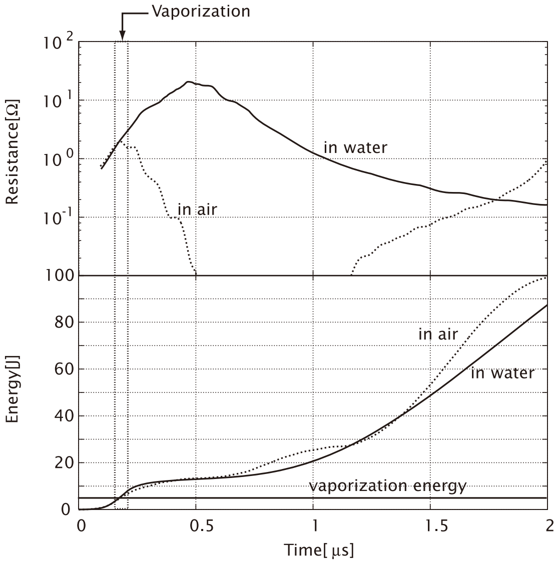


Fig. 3 Evolutions of the resistans (upper) and the input energy (bottom) of Al-wire (r_0 = 50 μm) explosion.

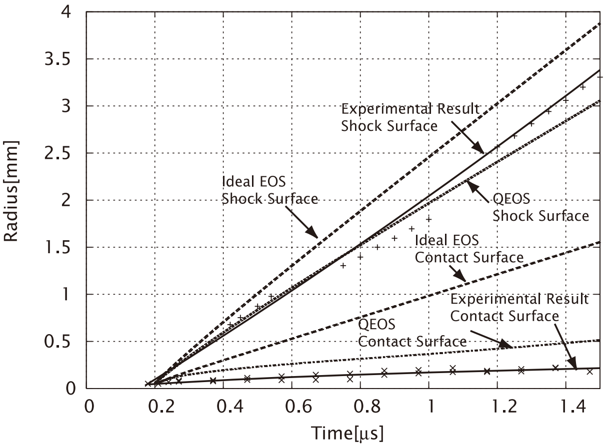


Fig. 4 Evolution of the shock wave and the plasma boundary. Solid lines denote the experimental results, and dotted lines show the numerical results.

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