Electromagnetically Driven Radiative Shocks and Their Measurements

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Experimental results on a generation of strong shocks in a compact pulse power device are reported. The characteristics of strong shocks are different from hydrodynamical shocks' because they depend on not only collisions but radiation processes. Radiative shocks are relevant to high energy density phenomena such as the explosions of supernovae. When initial pressure is lower than about 50 mtorr, an interesting structure is confirmed at the shock front, which might indicate a phenomenon proceeded by the radiative process.

Keywords: Radiative shocks, Pulse power, High energy density physics

I. INTRODUCTION

Strong shocks and related phenomena are universal in astrophysics, such as supernovae. The energy of shock is related to the neutrino luminosity[1] and agree with the observation on SN (SuperNova) 1987A. Especially, examining the structure of radiative shock is important to make clear the composition of elements vicinity of a supernova. If pressure, temperature and / or the other physical quantity of the supernova explosion are reproduced in a laboratory scale device, they can significantly contribute to astronomic observation and simulation of the stellar evolution.

It is well known that ordinary hydrodynamic shocks have a well-predictable discontinuous surface. However, characteristics of the radiative shocks are different from hydrodynamic Shocks'. The temperature behind shock is so high that radiative process dominates to form the shock structure. Temperature distribution is not discontinuous and has a precursor[2]. This precursor makes the X-ray emission of the shocked surrounding medium more complex[3].

Recently, using laser, the high energy density plasma is generated for astrophysics[3, 4]. The high energy density plasma is generated in laser irradiated target because it has characteristics of high intensity and directivity. Although laser can produce extremely high power, it is inefficient and too large equipment. In contrast with laser system, pulse power is more efficient and more compact. In this paper, experimental results on a generation of radiative shock in the pulse power is reported.

II. EXPERIMENTAL SETUP

It is the purpose of this study to generate strong shocks and investigate the radiative process in a laboratory scale pulse-power device. A plasma focus system is used for generating shocks. The concept of plasma focus is schematically shown in Fig.1. To make a strong and plain shock wave, cross section of the discharge area is gradually decreased with tapered electrodes and an acrylic guiding tube with constant cross section is located behind the electrodes. For generating strong shocks

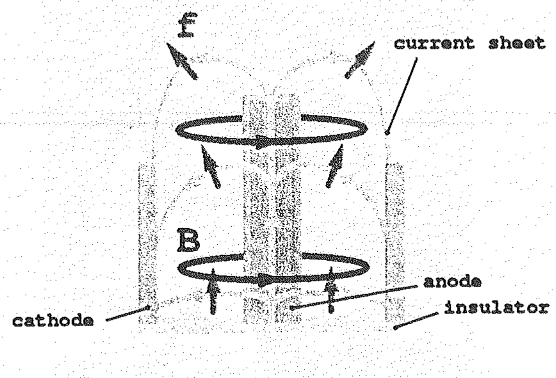

FIG. 1: Plasma focus system

such as radiative shocks, it is necessary that contact surface, fixed current sheet, push the fluid. A thin Al foil is mounted on the insulator to play the role.

The experimental setup of pulse power and its equivalent circuit are shown in Fig.2 and 3. 12 capacitors of 0.4 μF are arranged in a concentric pattern for reducing the inductance of the experimental setup. Charging Voltage is 20 kV and discharge current is measured by a Rogowski coil. Typical discharge current has LCR damped oscillation waveform, which is and shown in Fig.4. As shown, the peak discharge current is about 180 kA at 0.9 μs.

To change Mach number that indicate the strength of shock wave, initial pressure of gas is controlled by a rotary vacuum pump.

This configuration composed of the acrylic guiding tube is advantageous to measure the shock speed and enables us to make one-dimensional analysis. Shock speed is measured by a fast framing-streak camera through the acrylic tube.

III. EXPERIMENTAL RESULTS

The initial gas is air in this experiment. Initial pressure is measured by a pirani gage and a capacitance manometer. A typical experimental result is shown in Fig.5 at initial pressure of 300 mtorr. In the figure, 4 parts at 2100, 2300, 2500 and 2700 ns are framing images and the

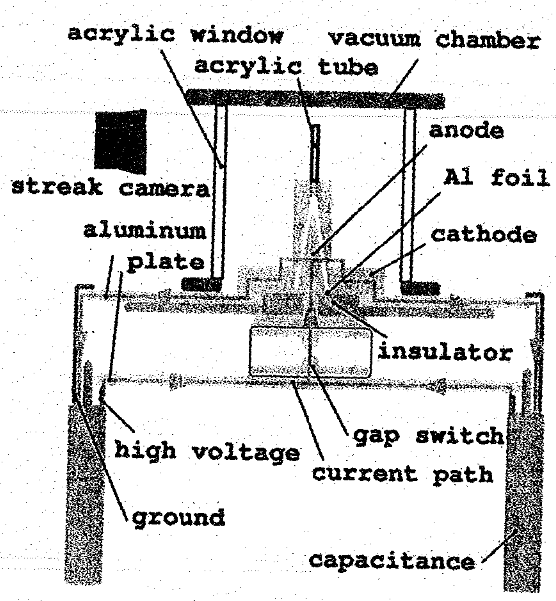

FIG. 2: A sketch of experimental setup

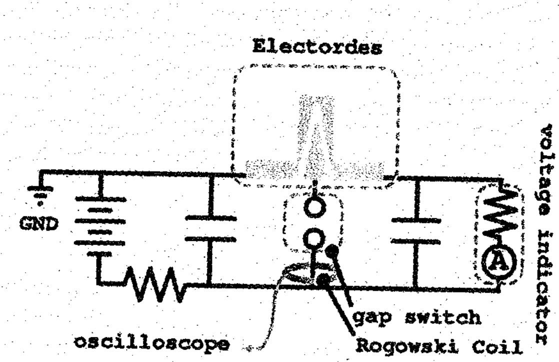

FIG. 3: Equivalent circuit of experimental arrangement

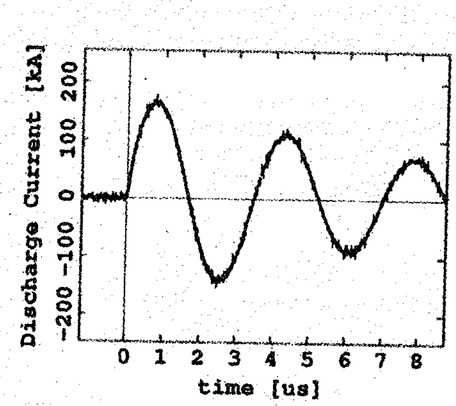

FIG. 4: Typical discharge current

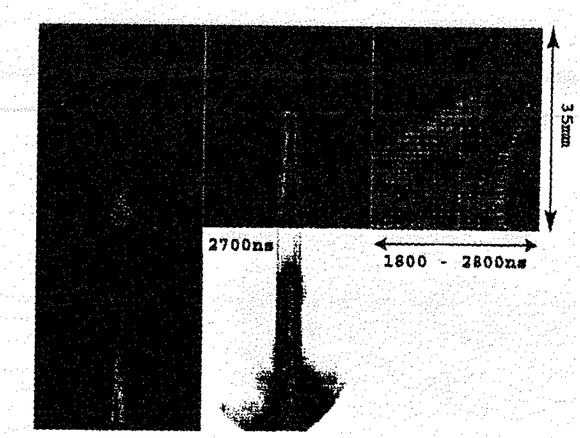

FIG. 5: An experimental result at initial pressure 300 mtorr

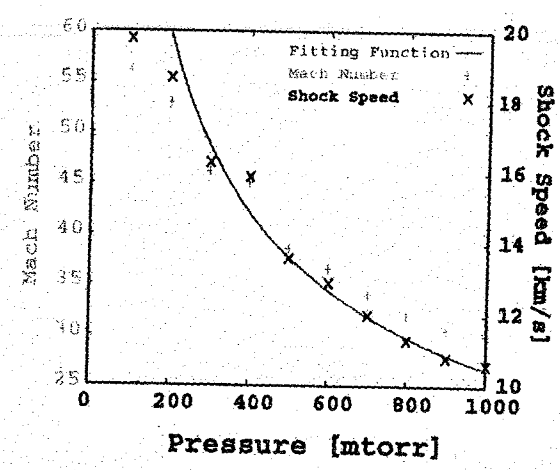

FIG. 6: Relation between initial pressure and shock speed

upper-right is the streak record of the discharge plasma through the guiding tube between 1800 and 2800 ns in Fig.5.

The shock speed is estimated to be about 16.2 km/s from the streak picture in Fig.5 at initial pressure 300 mtorr. The shock speed is evaluated as a function of initial pressure. A relation between the initial pressure and the shock speed is shown in Fig.6 in the range from 100 to 1000 mtorr. The Mach Number M is standardized by a sound velocity v_{N_2} of N_2 at room temperature, 300 K.

$$v_{N_2} = \sqrt{\left.\frac{\partial p}{\partial \rho}\right|_s} = \sqrt{\gamma RT} \approx 353[m/s] \qquad (1)$$

$$M \equiv \frac{D}{v_{N_2}} \qquad (2)$$

Where R is gas constant, D is the shock speed of experimental results. It is clear in Fig.6 that the lower the

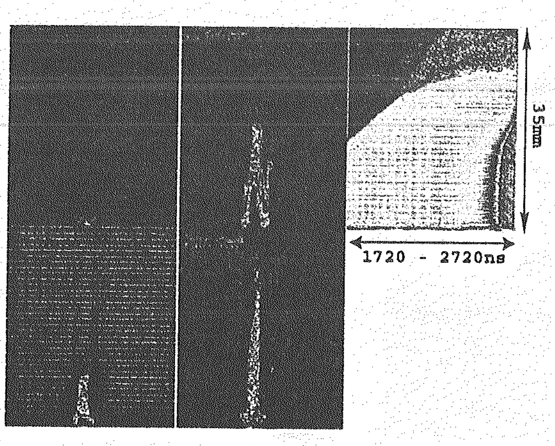

FIG. 7: An experimental result at initial pressure 50 mtorr

initial pressure is , the higher the shock speed is. The line is a fitting curve derived from the Rankine-Hugoniot relation. The Rankine-Hugoniot relation is

$$\frac{p_2}{p_1} = \frac{2\gamma}{\gamma+1}M^2 + \frac{1-\gamma}{\gamma+1} \approx \frac{2\gamma}{\gamma+1}M^2 \quad (3)$$

$$M \approx \sqrt{\frac{\gamma+1}{2\gamma}\frac{1}{p_2}}\frac{1}{\sqrt{p_1}} = \alpha\frac{1}{\sqrt{p_1}} \quad (4)$$

where, p_1 is the pressure in front of a shock surface, p_2 is the pressure behind the shock, γ is the specific heat ratio in air, $\gamma \approx \frac{7}{5}$, and α is a constant. The relation of Eq.4 by least-square fitting is shown with line in Fig.6. Here, α is evaluated to be 843.19. Using Eq.4, p_2 is estimated to be about 8.3×10^2 torr. Here, p_2 is the effective magnetic pressure, which is supposed to be dominated by the discharge current and the experimental set up. In this experiment, p_2 is assumed to be constant.

As shown in Fig.6, the experimental results can be fitted with the Rankine-Hugoniot relation appropriately between 200 and 1000 mtorr.

The experimental result obtained in lower than 100 mtorr is different from that in higher than 100 mtorr. The result obtained by the fast camera at initial pressure 50 mtorr is shown in Fig.7. In the figure, 4 parts at 1500, 1700, 1900 and 2100 ns are framing images and the upper-right is streak picture at between 1720 and 2720 ns.

We have to pay attention that the streak picture in Fig.7 can be divided into two parts. The shock speed is estimated to be about 24 km/s in the first part and 44 km/s in the second part. The shock speed in the first part, 24 km/s, corresponds to the scaling curve in Fig.6, but in the second part is different.

IV. DISCCUSION

The shock wave measured at pressure lower than 100 mtorr has an interesting structure. The shock wave can be classified by a criterion for shock speed D. The criterion[5, 6] for the radiative shock wave is derived from the Rankine-Hugoniot relations including radiation pressure and energy[7]. The Rankine-Hugoniot relations including radiation pressure and energy are

$$\rho_1 u_1 = \rho_2 u_2 \equiv \dot{m} \quad (5)$$

$$\dot{m}u_1 + P_{th1} + P_{rad1} = \dot{m}u_2 + P_{th2} + P_{rad2} \quad (6)$$

$$\dot{m}(\frac{\gamma}{\gamma-1}\frac{P_{th1}}{\rho_1} + \frac{1}{2}u_1^2) + u_1(E_{rad1} + P_{rad1}) = \dot{m}(\frac{\gamma}{\gamma-1}\frac{P_{th2}}{\rho_2} + \frac{1}{2}u_2^2) + u_2(E_{rad2} + P_{rad2}) \quad (7)$$

where ρ, u, P, and E are, respectively, density, velocity, pressure and the energy density. The subscript 1, 2, "th" and "rad" refer to the upstream flow, downstream flow, thermal element and radiation element. In the equations above, the radiation flux is not taken into account since outside the transition zone there is no gradient. The criterion, which characterize a full radiative regime, yields

$$D \geq D_{rad} = \left(\frac{7^7 k^4}{72a}\frac{n_1}{\mu_1^3}\right)^{\frac{1}{6}} \quad (8)$$

where k, a, n_1 and μ_1 are, respectively, the Boltzmann constant, the first radiative constant, the particle density, and the particle mass in the upstream region in front of the shock surface. However, the criterion assumes that matter and radiation fulfill the local thermodynaical equilibrium condition[6]. When the observed shock speed is more than the critical value D_{rad}, it satisfy the condition that ratio between thermodynamical pressure P_{th} and radiative pressure P_{rad}, $P_{rad}/P_{th} \sim 1$ in the downstream region behind of shock surface.

The experimentally obtained D and the critical speed D_{rad} in between 50 and 1000 mtorr are shown in Table I.

This estimation indicates that the condition lower than 100 mtorr satisfies the criterion for the radiative shock wave. The experimental result at $p_1 = 50$ mtorr, in which the interesting structure is confirmed, might indicate that it was proceeded by a radiation process.

V. SUMMARY

In this paper, experimental results on a generation of raditative shock in a compact pulse power device is reported. Results show that the lower initial pressure is,

TABLE I:
Reraltion between The experimentally obtained D and the critical speed D_{rad} in a initial pressure.

Initial pressure [mtorr]	D [km/s]	D_{rad} [km/s]
1000	13.0	23.5
700	12.0	22.1
300	16.3	19.4
100	19.8	16.1
50	23.9	14.3

the higher shock speed is. Electromagnetically driven shocks with M $\sim$ 50 are observed.

In operating condition with initial pressure of less than 50 mtorr, an interesting structure was confimed. This result might indicate that it was proceeded by a radiaiton process.

However, when the initial pressure is 50 mtorr, mean free path in front of the shock wave is $\approx$ mm. In this condition, an anomalous factor may affect the structure and speed of the shock wave because the characteristic length of experimental setup is $\approx$ mm. D_{rad} must be decreased to sufficiently satisfy the criterion for radiative shock wave. As D_{rad} is inversely proportional to the particle mass, we are planning to change the working gas to a heavier gas such as Xe in the future experiments.

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